Cook Engineering Design Center

Final Design Review Paper

Submitted in partial fulfillment of the requirements for

ENGS 90: Engineering Design Methodology and Project Initiation

Production Design for SafaPani

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Sponsored by

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EXECUTIVE SUMMARY

Nepal is facing an arsenic epidemic. Millions of its citizens unknowingly drink water contaminated with arsenic at levels higher than ten times the World Health Organization's (WHO) standard of safety. As one of the poorest countries in the world, Nepal lacks the resources and infrastructure necessary to treat its water supplies on a large scale. In response, VillageTech Solutions (VTS) and ENGS 89/90 teams have been developing the SafaPani filter. The electrocoagulation process of the SafaPani has been shown to lower concentrations of arsenic common in Nepal to below the WHO's safety standard. However, the SafaPani currently lacks a manufacturable model that incorporates the process into a housing designed specifically for families in developing countries.

Over the course of ENGS 89/90, we have focused on design for manufacturing, creating an elegant device, and minimizing the cost to produce and assemble the full product. With guidance from plastics manufacturers, DFM experts, and contacts in Nepal, the final SafaPani appliance has been uniquely designed around these three objectives.

The SafaPani consists of three custom molded plastic containers: a reaction vessel to house the electrocoagulation process, an outer shell that will hold the reaction vessel and filtration sand, and a reservoir tank to retain the clean water. Estimated die costs for the molds of these three containers in the U.S. are over $50,000. However, manufacturing costs after producing a mold approach material cost, and in quantities of 10,000 devices or higher, the cost of the mold factors minimally into the unit cost of a device.

Testing using a fully functioning prototype built from off the shelf components confirmed that the SafaPani design satisfies each identified requirement and associated specification. Finite element analysis on a computer model of the SafaPani confirmed the structural integrity of the product, and user testing has shown that it is intuitive and simple to operate.

Looking to the future, there is still room for optimization of our ideal design, but the first step to be taken is to perform arsenic testing on our prototype, to ensure that it effectively filters arsenic to below the WHO standard of 10 ppb. Successful filtration results will be the final hurdle in validating the function our design. Building a small number of our working prototype units will allow VTS to quickly and cheaply test the design in Nepal, and acquire usability data to further validate and perhaps enhance the design.

We are providing VTS with the following four deliverables:

- SolidWorks design of a custom-molded design housing the SafaPani process.
- Assembly instructions for design.
- Working prototype of design that satisfies the identified specifications.
- Pictorial user guide showing the user how to safely operate the SafaPani.

We have achieved all four of these deliverables, with a main focus on the moldable design, which is central to moving the device towards production, and have done all we can to validate the effectiveness of our product inside the timeframe of ENGS 89/90.

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BACKGROUND

Naturally occurring arsenic in groundwater is an issue on every continent. A study in 2007 revealed "over 137 million people in more than 70 countries are probably affected by arsenic poisoning of drinking water" (Arsenic 2007). Ingestion of high levels of arsenic leads to a disease called arsenicosis. Symptoms can take years to appear and include "color changes in skin, painful hard patches on palms and soles of feet, and some forms of cancer" (Water-related Diseases 2014).

While arsenic ingestion is a serious problem worldwide, it is a catastrophe in Nepal. Some areas of Nepal have levels of arsenic in their groundwater over 500 parts per billion (ppb), or 50 times the World Health Organization's standard of safety. As one of the poorest countries in the world, Nepal lacks the resources and infrastructure necessary to treat its water supplies on a large scale. Therefore, Nepal's citizens need a widespread, cheap, and low maintenance solution to remove arsenic from their contaminated water.

PROCESS OVERVIEW

VillageTech Solutions (VTS) has been developing the SafaPani, a low-cost household arsenic filtration appliance that utilizes electrocoagulation to filter arsenic from water (Appendix A). During electrocoagulation, two iron electrodes release iron ions into the water through electrolysis, which react with hydroxide to form iron (III) hydroxide. Arsenic then complexes with the iron (III) hydroxide and forms a precipitate, which can be filtered out through sand. With this chemistry at its heart, the full SafaPani process is summarized in Figure 1. Previous ENGS 89/90 groups have validated electrocoagulation as an effective means of arsenic filtration (Appendix B); however, their system lacked a manufacturable housing that is cheap, simple, and durable enough to succeed in a rural Nepalese home.

Figure 1: A flow chart of the SafaPani process, transforming contaminated water into clean water.

ECONOMIC AND SOCIAL CONSTRAINTS

The median income in Nepal is around \$700/year and is even lower in our targeted region, Nawalparasi (Nepal 2014). Additionally, our end users are very self-sufficient, using their limited resources to purchase essentials such as kerosene, fertilizer, and batteries. Therefore, minimizing the production cost of our product is a pivotal factor in generating demand. Furthermore, our target users live in very rural environments and have limited opportunities to obtain new parts for repairs or routine maintenance (Appendix C). As a result, our product is durable and reliable.

PROBLEM AND NEED STATEMENT

VTS has proved that their unique electrocoagulation method is both simple and effective at reducing arsenic concentrations to safe levels. However, VTS needs an inexpensive, user-friendly, and manufacturable design to house its arsenic filtration method that will succeed in Nepal.

Requirements and Specifications

The design of SafaPani must meet the required manufacturing, function, and daily use criteria for a product manufactured in Calcutta and used in Nepal. First, it must be cheaply manufacturable in order to be practical to distribute to the villagers of Nepal. Second, it must be easy to use and aesthetically pleasing to our intended users so that it is adopted quickly into the daily task of collecting water. Third, it must require minimal maintenance and resist wear in order to maximize device longevity. Table 1 summarizes the identified requirements and associated specifications necessary to meet these design objectives.

Requirement	Specification	Ideal Value	Tolerance Limit
Manfuacturable			
1. Minimize cost of manufacturing	1. Cost of Goods Sold	< $30	-
2. Easily Transportable	2. System weight without water or sand	< 15 kg	< 20 kg
3. Manufacturable in Calcutta	3. Materials are sourceable in Calcutta	-	-
Function			
4. Powered	4. Battery powered	12V battery	-
5. Stable	5. Can withstand a force applied from the side or above	> 150 N	> 100 N
6. Sand Filter	6. Filtration sand height	> 20 cm	> 19.5 cm
Daily Use			
7. Safe	7. Reliably filter arsenic	< 5 ppb	< 10 ppb
8. Hold a family's daily usage	8. Reservoir size	65 L	10 L
9. User friendly for Nepalese	10. Time required to change sand	< 10 min	< 20 min
	11. Time required to change electrodes	< 10 min	< 15 min
	12. Time required to teach how to use	< 5 min	< 10 min
	13. Clearance under device to fill up water containers	> 0.3 m	> 0.2 m
10. Durable	14. Long lifespan	> 5 yr	1 yr
	15. Maintanence needed	Monthly	Biweekly
11. Fits well in Nepalese home	16. Footprint	$< 0.25\ m^2$	$< 0.4\ m^2$
12. Water appears clean	17. Water is free of particulates, smell, and discoloration	-	-
13. Fits well into how Nepali people currently gather water	18. Reaction vessel size	15 L	10 L

Table 1: A breakdown of the requirements and associated specifications our design must meet to satisfy the project objectives.

Deliverables

We are providing VTS with the following four deliverables:

- SolidWorks files of a custom molded housing for the SafaPani process
- Assembly instructions for the design
- Working prototype of the design that satisfies the identified specifications
- Pictorial user guide showing the user how to safely operate the SafaPani

Delivering these four items will enable VTS to begin the process of bringing electrocoagulation to Nepalese citizens as a means to filter their arsenic contaminated water. We have achieved all four of these deliverables, with a main focus on the moldable design, which is central to moving the device towards production.

SOLUTION

Throughout the course of the project, we have worked with manufacturing design and molding experts to create a device capable of meeting all of our requirements and specifications. The final product is shown in Figure 2.

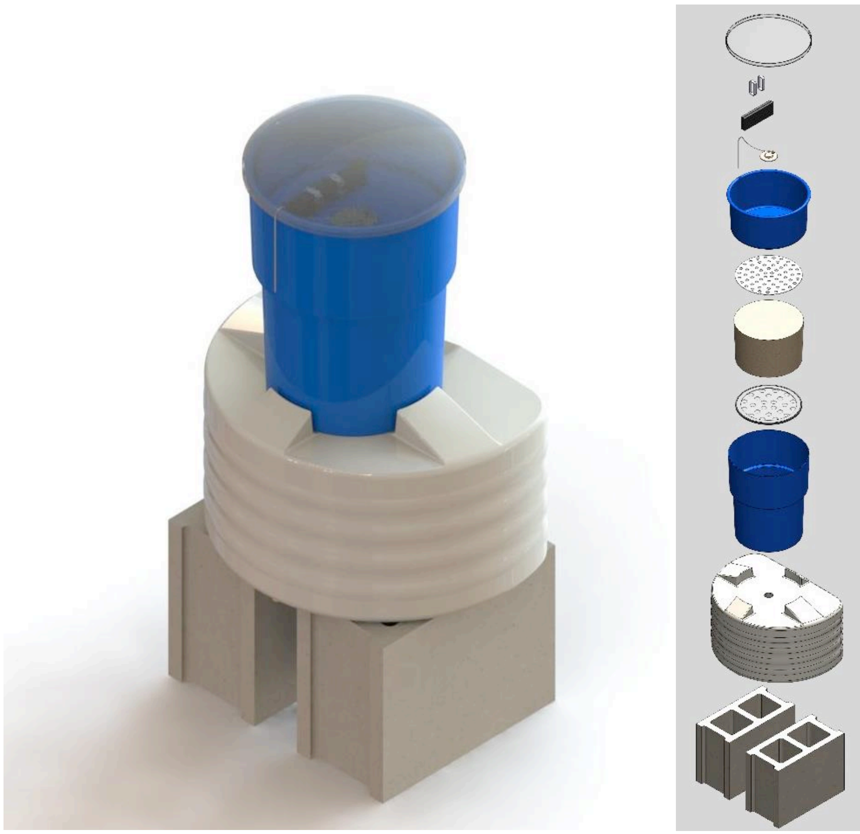

Figure 2: Assembled device and exploded diagram detailing each component of the SafaPani design.

Our design consists of three molded plastic containers: a reaction vessel that houses the electrocoagulation process, an outer shell that holds the reaction vessel and the filtration sand, and a 65 L reservoir tank that holds clean water (Alternative views and dimensioned drawings for manufacturing can be found in Appendices D and F). The containers are designed such that the reaction vessel nests inside the shell to decrease footprint and add stability (Spec. 16). The inner reaction vessel sits on the built-in shelf of the shell, and the reservoir holds the shell firmly upright with four raised braces. Each container is shown in Figure 3. Manufacturing and assembly instructions can be found in Appendix F.

The 15 L reaction vessel is a wide bucket with a lip that curves over the edge of the shell (Spec. 18). The lip of this bucket fits over the rim of the shell, so if the vessel is overfilled or water is spilled, the device will shed the water and not contaminate the other tanks (Spec.7). The lip has the added benefit of creating a handle with which the reaction vessel can be lifted out of the shell to access the sand for maintenance.

The reaction vessel is best manufactured through injection molding due to its wide open top and inner complexities. Dana Howe, an experienced engineer at the injection molding company GW Plastics, reviewed our design and confirmed that injection molding is the optimal

method of manufacture (Appendix G). He recommended a minimum draft angle of 2˚ and a wall thickness of 2.5 mm with a tolerance of 0.2 mm, which we have integrated in our design.

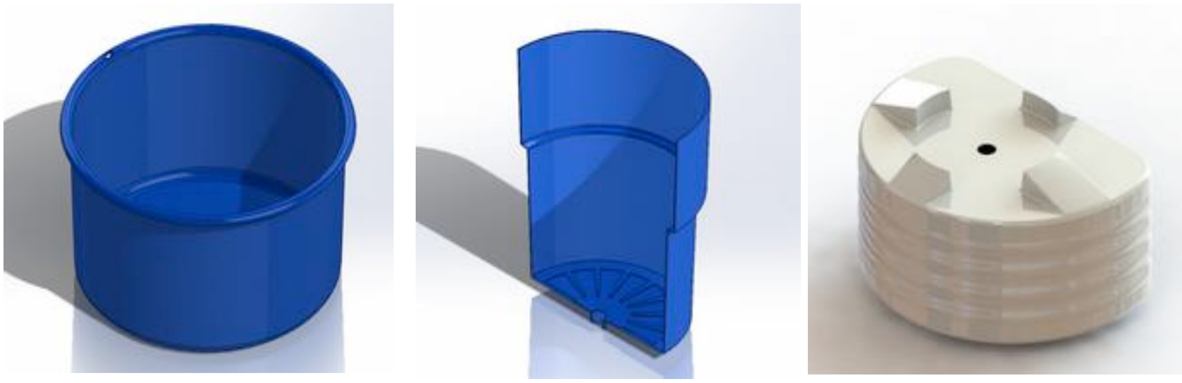

Figure 3: The three main containers of the SafaPani: the reaction vessel, shell, and reservoir.

A flapper valve in the bottom of the reaction vessel is used to drain the water into the sand filter after the electrocoagulation process is complete. It is recessed in the bottom of the bucket to ensure all of the water drains. The user must pull the nylon cord attached to the flapper to release the water into the sand filter once the reaction is complete.

The electrodes are secured to the bottom of the reaction vessel with strips of Velcro screwed into the bottom of the bucket with 8-32 nylon screws and nuts with rubber washers. The Velcro securely holds the iron bars vertically while still providing access to remove and replace them, so that the hydrogen bubbles produced between the electrodes can escape upwards (Spec. 11). O-rings with a cross-sectional diameter of 2.5 mm are placed around the electrodes to keep them properly spaced apart, even with degradation of the iron over time.

The electronics are potted in epoxy and screwed to the inside wall of the reaction vessel with 8-32 nylon screws, nuts, and rubber washers. The electronics are placed near the rim of the reaction vessel so the LEDs can be easily viewed through the clear lid to notify the user. Two wires connect the potted electronics to the electrodes and two wires lead from the electronics to the battery external to the device.

The shell is a tall bucket in which the reaction vessel nests. The bottom section is a smaller diameter than the top to create a ledge on which the reaction vessel can rest. The sand is stored in the base of this container beneath the reaction vessel so that the sand is easily accessible to the user by lifting the reaction vessel out of the shell (Spec. 10). With the height of sand constrained to a minimum 20 cm, minimizing the diameter of the sand decreases the overall weight.

Mr. Howe recommended that the shell be manufactured through injection molding as well with 2.5 mm thick walls and a tolerance of 0.2 mm. It has the minimum draft angle of 2˚ to make the most stable shape that is still injection moldable. The shell is 42 cm tall and with an upper diameter of 17.5 cm and smaller bottom diameter of 15 cm, with the decrease in diameter occurring 18 cm from the top. A slope is molded into the bottom of the shell to allow the water to drain out easily. A raised ring along the inside of the bottom of the shell with spokes pointing to the drain will provide support for the sand screen while also increasing surface area for the water to drain out of the sand.

The sand screen rests on the bottom of the inside of the shell and retains the sand while allowing the filtered water to pass through. The sand screen fabric is 100% nylon with a rip-stop weave. The fabric is held between two disks of high density polyethylene (HDPE) and fixed with urethane-based glue. One piece of the HDPE is shaped as an open annulus to allow the least

impedance to water flow, while the second piece is a disk with many 3 cm diameter holes to provide structural support for the sand. A low-cost, FDA approved rubber is adhered with glue around the disk to form a tight seal to the inner walls of the shell. The 20 cm of sand rests on top of the sand screen (Spec.6). This 20 cm height was determined optimal for filtration by the previous ENGS 89/90 team (Appendix B). On top of the sand rests a dispersion plate manufactured by being stamped out of a sheet of HDPE.

A transparent, domed lid fits over the top of the reaction vessel and snaps into place. There are grooves in the lip of the reaction vessel to provide a channel for the wires and flapper valve pull cord to exit the device without affecting the ability of the lid to close securely. The dome shape of the lid discourages users from placing objects on top of the device and also sheds water. The lid will be thermoformed out of clear polyethylene terephthalate.

The shell rests on the rotomolded reservoir tank. Our tank design is similar to an existing rotomolded tank found in Calcutta (Appendix H), albeit with a 65 L capacity and a semi-cylindrical shape to fit against a wall (Spec. 8). It is 30 cm tall with a radius of 30 cm and has a wall thickness of 3 mm. It has horizontal ribbing for structural support as well as four angled supports to brace the shell. A valve at the bottom of the reservoir allows the user to dispense the water when needed. The reservoir tank is raised on a cinderblock stand to allow for adequate spacing to fill a large cooking pot underneath the output valve (Spec. 13).

The full device is 0.75 m tall and will sit 0.3 m off the ground with the stand, bringing the full height to about 1 m, which is slightly above the hip level of an average adult. Minimizing the height of the device has been a driving objective, as Nepalese citizens are required to fill the reaction vessel from the top with 15 L (15 kg) of water.

Safety and reliability are paramount to the successful use of our device. A household water filter has the potential for accidental consumption of arsenic and thus demands precision and care when operating the device. As with any manufactured device, there are associated risks and reliability issues, which we have addressed in Appendix I. When operated according to the pictorial user manual, though, our device successfully takes in contaminated water, and outputs clean water that is free of debris, color, and odor (Spec. 17).

Beyond meeting our design requirements and specifications, the manufacturing costs are minimized due to utilizing industry standards for molding methods and using common shapes and materials for cut pieces. The light-weight plastic containers make the device easily transportable when empty (Spec. 2), and also are durable for the 5 year lifespan of the device (Spec. 14). Every manufacturing step we have deemed necessary, is possible in Calcutta (Spec. 3). The device is battery powered and holds a family's daily volume of water (Spec. 4). The shape and supports built into the device make it safe and stable (Spec. 5). The simplicity of the design aids in user-friendliness, and ease of maintenance (Specs. 10, 11, 12, 15). The wide open top allows users to easily pour water from their collection bucket into the reaction vessel. The flat side of the tank allows the device to be put against a wall maximizing storage capacity while still minimizing footprint (Spec. 16). Finally, we have confirmed the compatibility of our full size design with the aluminum molds required for injection molding with draft analysis in SolidWorks (Spec. 3) (see Appendix E).

Electronic Circuit

The SafaPani system requires an electronic circuit to control the electrocoagulation process. The following list outlines the objectives of the circuit.

1) Controls the current to the two iron electrodes submerged in the reaction vessel.
2) Measures current through the electrodes and shuts the process off at a designated coulomb limit. Doing so enables the SafaPani to introduce a precise amount of iron into the water in order to consistently filter arsenic.
3) Measures the battery voltage and shuts off the system when the battery is low.
4) Signals to the user when the reaction vessel is undergoing electrolysis, when it waiting for the iron to mix with the arsenic, and when the process is over. This lets the user know when it is time to open the valve from the reaction vessel to the sand filter.

Figure 6 shows the circuit schematic and board layout of the printed circuit board, as well as an overview of the microcontroller process used to accomplish the four tasks listed above. The board is encased in a clear epoxy that waterproofs the circuit and allows the user to see the signal LEDs on the board. A more detailed description of the circuit design, including a user manual and the microprocessor code, can be found in Appendices M and N, respectively.

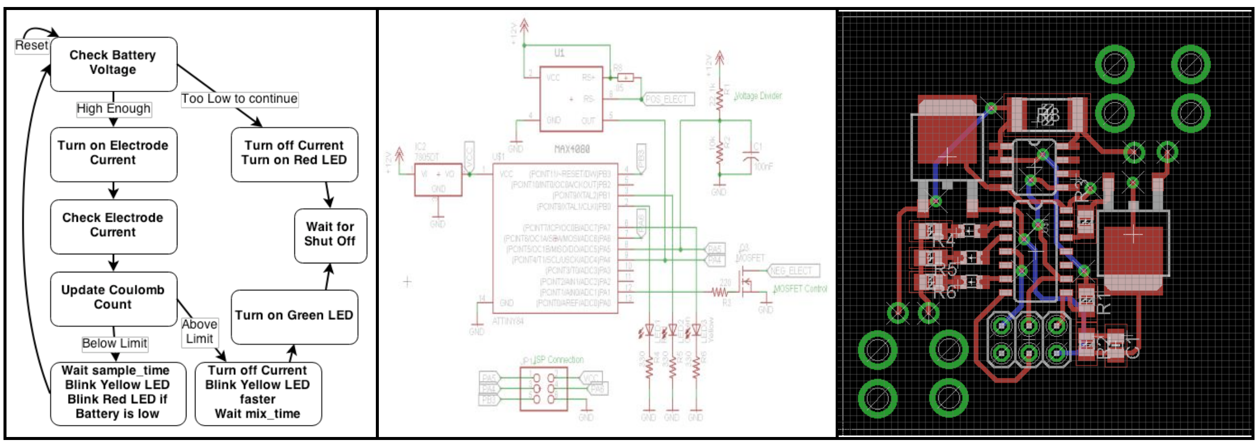

Figure 6: Microprocessor flowchart, circuit schematic, and printed circuit board layout.

Testing

To validate that the SafaPani design described above satisfies each required specification, we performed qualitative and quantitative tests. The following section describes each test and its results.

Finite Element Analysis

A finite element analysis was conducted in SolidWorks to validate the structural integrity of the design. The results can be found in Figure 4. The maximum weight of the full device (with 15 L of water in the reaction vessel plus 20 cm of wet sand in the shell) weighs about 45 kg and creates a load of 506 N on the reservoir tank. Under these loading conditions the reservoir will deform 1.5 cm downwards in the center of the top, but will not fail. The maximum stress endured by the tank is about 12.5 MPa. With a yield strength of HDPE is 26 MPa, our design has a factor of safety of 2.08. With the weight and shape of the device, a force of 100N applied from the side to the top of the device would be required to push over the shell.

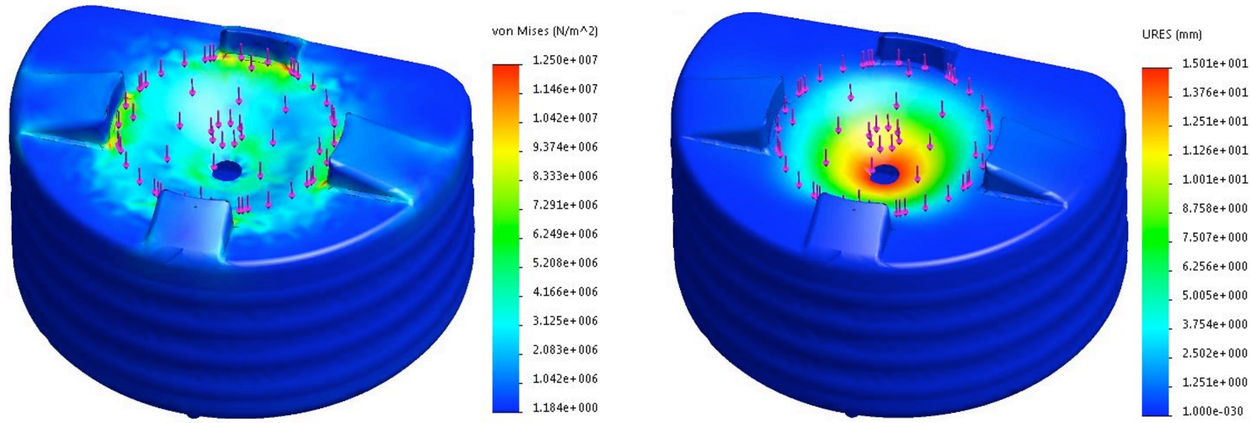

Figure 4: FEA analysis of the reservoir tank. Left: Maximum stress of 12.50 MPa. Right: Maximum deflection of 1.501 cm as a result of the applied load of a full reaction vessel and shell.

Sand Screen Fabric

One of the main design challenges lay in creating a method to contain the sand while allowing water to pass, and be strong enough to withstand the weight of a 20 cm high column of sand. With these two design requirements in mind, we examined the sand permeability and flow rate performance of cotton, polyester, polyester-cotton, nylon, agricultural, Weed-Block fabric, and mesh screening. In order to test a fabric's ability to contain sand, a pouch was constructed out of each fabric and a constant amount of sand was added. Water was passed through each pouch of sand and collected to determine if any sand escaped. In order to decide which had the optimal flow rate, 1 L of water was timed while it was poured through each sand pouch (Appendix J). The agricultural fabric was the strongest but had the slowest flow rate. The Weed-Block fabric had the fastest flow rate, however, it was prone to inelastic deformation under stress, so it was also rejected. Therefore, the only materials that satisfied our two design requirements were cotton, nylon, polyester, and polyester-cotton fabric. However, cotton is a naturally grown fiber and is subsequently prone to degradation in the warm, wet areas it would be placed. Furthermore, both polyester and polyester-cotton fabric had high flow rate and durability; however, they both ended up retaining water and required a long time to dry. Comparatively, nylon not only had a high flow rate and durability, but it also was quick-drying. Therefore, we chose nylon fabric over a polyester or polyester blend fabric to use in our final design.

User Testing

In order to validate and improve upon our design, we asked volunteers to carry out tasks that would mimic both daily use and necessary maintenance. In our first two tests, the subjects were asked to replace the electrodes and change the sand. In order to measure the ease of this maintenance, we timed the users with the idea that shorter time correlates to ease of replacement (Appendix K). In our next test, the subjects were asked to use our device as intended by following a pictorial step-by-step guide in order to obtain feedback on the clarity of our instructions (Appendix L). We also determined average flow rates for processing the 15 L of water that each subject filtered, which is displayed in Figure 5. After completion, the subjects were surveyed on the ease of maintenance, intuitiveness, ease of use, and helpfulness of the pictorial guide. Finally, the subject was asked one way in which they would improve our device to not only narrow down problem areas in our design, but also highlight any unique problem we

may have overlooked (Appendix K). Ultimately, subjects thought that our device was fairly intuitive and easy to use.

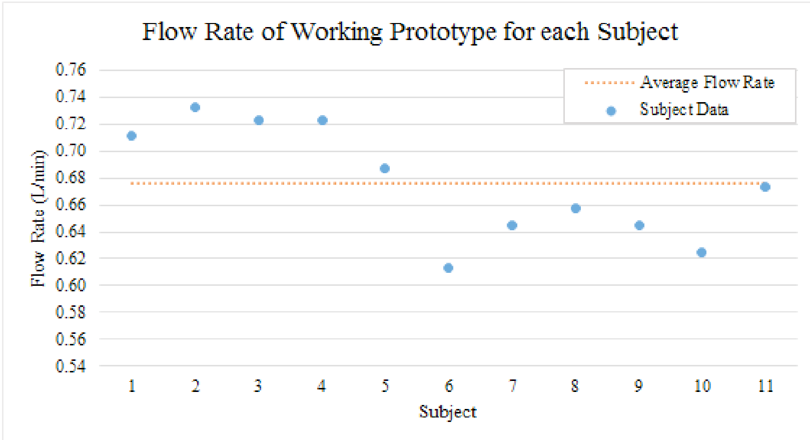

Figure 5: Flow rate results of the working SafaPani prototype. The average flow rate over all subjects was 0.676 L/min.

WORKING PROTOTYPE

Our prototype represents the ideal, moldable design constructed to the best of our ability without utilizing custom molding. Since the estimated die costs for injection and rotomolding are over $50,000, we decided that we would produce a highly representative and fully functioning prototype with off the shelf components (Appendix O). In this way, we avoided spending the substantive cost of tooling the mold before user testing revealed any necessary changes in the design. In Figure 8 below the ideal model and the working prototype are displayed side by side. As one can see, the general shape of the molded design is conserved in the prototype. The reaction vessel still nests within the shell, with the curved lip of the reaction vessel extending over the edge of the shell. Additionally, the shell in the working prototype contains the dispersion plate, sand screen, and sand found in the moldable design. To replicate the topography of the bottom of the shell in the molded design, marbles were used. However, the overall height of the prototype is taller than that of the molded design. The price of the working prototype is $127.19 (Appendix P).

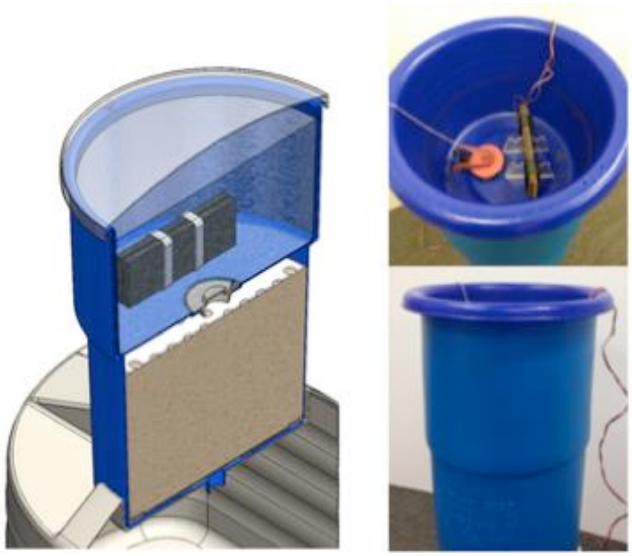

Figure 8. Ideal, moldable design and working prototype side by side.

ECONOMICS

After the model was researched, tested, and finalized, quotes for each component of our design were compiled in order to determine a final Bill of Materials for our device. The summarized unit cost for each component in our final design is shown in Table 2.

Bill of Materials			
Item	Description	Quantity	Cost per Device
Reaction Vessel	Cost of molding the reaction vessel excluding mold tooling expenses	1	$3.15
Shell	Cost of molding the shell excluding mold tooling expenses	1	$5.15
Reservoir	Cost of off the shelf tank in India	1	$10.00
Iron Electrodes	Raw material needed for electrocoagulation process	2.84 lbs	$0.29
Velcro	Secures electrodes	2 x 5 in. paired strips	$1.67
Flapper Valve	Allows resealable connection between reaction vessel and sand filer	1	$3.16
8-32 Nylon Screw	Secures electrode holder to reaction vessel	2	$0.11
8-32 Nylon Nut	Secures electrode holder to reaction vessel	2	$0.12
Rubber Washers	Seal screw hole in reaction vessel	4	$1.20
0.06" PETG Sheet	Thermoformed Lid: Covers reaction vessel to prevent debris entry	0.06" x 14" x 14"	$2.85
String	Secures lid when refilling reaction vessel	2'	$0.20
1/8" Thick HDPE Sheet	Dispersion Plate: Disperses water over sand filter to prevent channeling Sand Screen Holders: Secures and supports nylon fabric sand filter	1/8" x 27" x 27"	$3.69
Nylon Fabric	Fabric used for sand screen	12.5" x 12.5"	$0.81
A50 Silicone Rubber Tube	Provides watertight seal for sand screen	1/4" ID x 1/2" OD x 3.2'	$6.94
Gorilla Glue	Adhesive used to construct and seal sand screen	15 mL	$0.10
Electronics	Total cost for all electronic components in device		$4.81
Sand	Sand used to filter arsenic-iron precipitate	50 lbs	$1.20
Cinder Block	Stand to raise device to appropriate height	2	$1.50
		Total (US)	$45.45
		Total (Calcutta)	$27.27

Table 2: A detailed Bill of Materials for the molded SafaPani device. Unit pricing for a production run of 1000 devices in the U.S. and adjusted for Calcutta is shown (Spec.1).

In order to obtain estimates for injection molded parts, we consulted with our manufacturing contact, Dana Howe. The additional tooling and assembly estimates are compiled in Table 3 to generate a total cost per 1000 units of our device. We consulted with our established manufacturing contact in Calcutta, Jaydeep Dasgupta, for costs of parts purchased in India. Our sponsor, who has conducted business in Calcutta, has approximated the cost

adjustment factor of goods and services between the U.S. and Calcutta as a 50-70% discount. Thus, we will convert our prices for production determined in USD by a factor of 0.6 to estimate the total cost in India.

Cost of Goods Sold		
Item		Cost (Qty. 1000)
Cost of production (excluding tooling)		$45,449.67
Tooling cost		
Reaction vessel	+	$17,000.00
Shell	+	$22,000.00
Cost adjustment for India production	×	0.60
Total manufacturing cost		$50,669.80
Assembly		
Labor rate ($/hour)		$2.00
Labor time(hours)	×	500
Total assembly cost		$1,000.00
Packaging		
Reaction vessel		$280.00
Shell		$480.00
Total packaging cost		$760.00
Total cost (Calcutta)		$51,429.80

Table 3: A breakdown of the costs associated with molding, tooling, and assembly. By incorporating these costs with our Bill of Materials, we can estimate the total cost of producing 1000 units of our device.

PATHWAY TO SOLUTION

The process of developing, building, and validating the SafaPani design involved research, consultations, and most importantly, design iterations. We began by researching the problem of arsenic contamination in Nepal in depth, including the state of the art already designed to solve it. The shortcomings of the Sono Filter and Kanchan Filter, two popular competitors, were readily apparent (Appendices C and Q). For example, both have brittle and weak features which protrude from the device and could shear off. Previous ENGS 89/90 teams and Dartmouth Humanitarian Engineering (DHE) have done a lot of work in solving these issues. The most recent iteration of the Dartmouth design used two large nested buckets.

Considering these designs, it was apparent that plastic molding would be large part of the project. As a result, part of our research involved investigating plastic manufacturing processes, specifically injection molding, blow molding, and rotational molding. Each process has its own advantages, general practices, and common materials. Consulting specialists such as Dana Howe and Professor Ulrike Wegst gave us expert opinions and guidance on these topics (Appendix R). Using the Cambridge Engineering Selector (CES) software, we were able to evaluate over 100 materials based on their relevant properties (Appendix S). Our requirements whittled the list to just 19, and helped us select HDPE as the cheapest options for many of our parts.

In parallel with researching manufacturing processes, we followed a regimented design strategy to develop the form and function of each piece of the SafaPani. Figure 9 summarizes the steps involved in our process. The arrow from testing back to brainstorming highlights the importance of the many iterations we have made to arrive at our final solution.

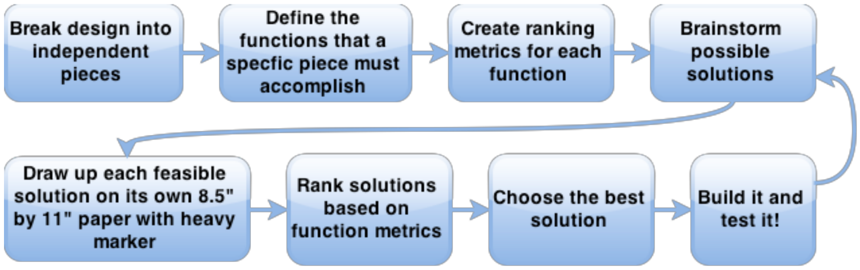

Figure 9: The high-level design method we used to develop each component of the SafaPani.

Each piece of the SafaPani underwent a design progression, improving with input from our sponsor, expert consults, and testing results. Figures 10 and 11 show the many overall SafaPani forms and corresponding prototypes used to test specific pieces of them. The volume, footprint, and material of the design changed immensely throughout the project, as we became more knowledgeable about the culture and needs of our user. For example, reducing the overall batch size and reservoir volume to 15 L and 65 L respectively better fits into the average Nepalese household daily use requirement.

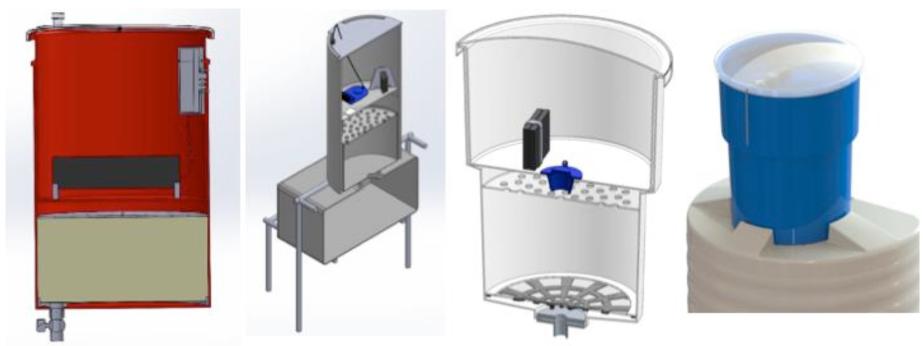
Figure 10: Progression of SolidWorks modeling: 2012 ENGS 89/90 final model (image from Stefan Deutsch), our PDR SolidWorks model, our CDR SolidWorks model, and our final SolidWorks model.


Figure 11: Progression of physical prototypes: DHE 2013 prototype, VTS 2014 summer prototype, our PDR prototype, and our final working prototype model.

Each form shown above also requires a holder for the electrodes and a water-permeable sand screen to contain the sand. For the most part, these pieces are independent of the overall form, and were therefore optimized independently. The electrode holders were designed to be simple and strong, while also allowing for easy removal of the electrodes. The sand screen's main design challenge lay in designing a simple solution that would let water, but not sand, to pass. Figures 12 and 13 show the main design progressions used to reach the final, elegant solutions.

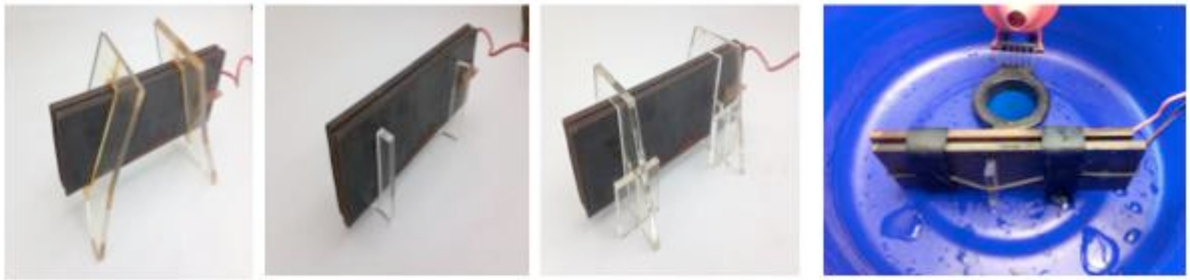

Figure 12: Progression of Electrode Holder design: Angled laser cut rectangles with feet designed by VTS with 2 mm center section. U-shaped with separate 2 mm shim. Trapezoidal clips with 2 mm nub and perpendicular stabilizers. Velcro straps screwed into floor of reaction vessel and electrodes spaced by a 2 mm diameter O-ring.

Figure 13: Progression of Sand Screen design: Four types of tubing tested; silicone A35 (on hardness scale), silicone A40, rubber latex A35, and neoprene A61. Two structural support options; disk with 1.5" diameter holes, or 'X'. Fully assembled sand screen option with rubber latex A35 and 'X' style support.

These iterations led to our final deliverable: a moldable, nested-bucket design that conforms to the unique pressures and constraints of life in rural Nepal. The progression of our work from the beginning of ENGS 89 and to the end of ENGS 90 leaves the SafaPani as a manufacturable product.

NEXT STEPS

Dartmouth students have worked on various aspects of the SafaPani project since 2009. Our contribution to the system has been to create a manufacturable design to house the validated electrocoagulation process. We have succeeded in this goal and validated the effectiveness of our product during ENGS 89/90. However, there is always room for optimization. Possible further investigations include:

1) Recessing the valve in the reservoir tank to shield from shearing
2) Manipulating the form of the top of the reservoir tank to inhibit contaminants from entering the tank such as with a ridge or trough
3) Manufacture the printed circuit board with holes for screws to eliminate an assembly step
4) To improve the seal on the sand screen, an oversized ring of rubber sheeting could be inserted between the two plastic disks such that the overhanging rubber edge deforms against the walls of the shell to create a seal
5) Completely minimize the cost of the device

The next step that needs to be taken to move towards production is to perform arsenic testing on our prototype to ensure that it effectively filters arsenic to below the WHO standard of

10 ppb. DHE is planning to conduct such a test in the coming spring of 2015. Successful arsenic filtration results will fully validate the functionality our design.

Another step is to perform field testing in Nepal and to learn more about how the SafaPani will fit into a villager's home. Building a small number of our working prototype units will allow VTS to quickly and cheaply test the design in the real world, while acquiring usability data to further validate and perhaps enhance the design. Ideally, VTS will bring these prototypes to Nepal in the summer of 2015. In parallel with field testing, DHE should begin to apply for grants or fundraise for the relatively large cost of molding and tooling for molding the three main pieces of the design and the initial production run.

Successful small scale tests of the working prototype in Nepal can provide VTS with the confidence to pay for the prototype molds necessary to create the fully custom SafaPani design. The production of these molds permits VTS to cheaply fabricate the reaction vessel, shell, and reservoir, and begin the process of bringing the SafaPani into the hands of the people who need them most.

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Appendix A: Electrocoagulation Theory

Electrocoagulation can be viewed as a four-step process once a current is placed through the electrodes:

1. Iron is oxidized at the anode and released into solution.

$$Fe_{(s)} \rightarrow Fe^{2+}_{(aq)} + 2e^-$$

2. Water is separated into hydrogen gas and soluble hydroxide ions through electrolysis at the cathode.

$$2H_2O_{(l)} + 2e^- \rightarrow H_{2(g)} + 2OH^-_{(aq)}$$

3. Iron is oxidized further while in solution. With the OH- being made at the cathode, this reaction is kept at a reasonably neutral pH, which is ideal for the formation of Fe^{3+} ions.

$$\tfrac{1}{2} H_2O_{(l)} + \tfrac{1}{4} O_{2(aq)} + Fe^{2+}_{(aq)} \rightarrow Fe^{3+}_{(aq)} + OH^-_{(aq)}$$

4. Iron ions react with soluble hydroxide in solution to form an insoluble precipitate. These flocs increase in size with time as the Fe(OH)3 continues to precipitate onto existing flocs. Throughout this process, arsenic is also trapped and bound to these larger $Fe(OH)_3$ flocs and therefore removed from the water.

$$Fe(OH)_{3(s)} + AsO_4^{3-}{}_{(aq)} \rightarrow [Fe(OH)_3 * AsO_4^{3-}]_{(s)}$$

Rate of reaction for the oxidation of iron is directly related to Faraday's First Law of Electrolysis:

$$dn = \frac{I * dt}{F * z}$$

where dn is the rate of moles of iron dissolved, I is current through the anode, F is Faraday's constant, and z is the valence of the iron. Experimental literature observes closely followed reaction rates based on a theoretical value for z = 2.

We can also define a charge loading parameter seen below:

$$q = \frac{I * t}{V}$$

where q is the amount of charge through solution per volume treated. Combining charge loading with Faraday's Law above gives:

$$d(Fe) = \frac{q}{F * z}$$

This equation is useful for modeling an electrochemical batch reactor since charge loading can be seen as directly related to iron dosage in solution. However, oxide buildup on the electrodes over time can degrade the quality of the reaction and dissolve less iron than theoretically predicted.

Appendix B: Previous ENGS 89/90 Testing and Optimization

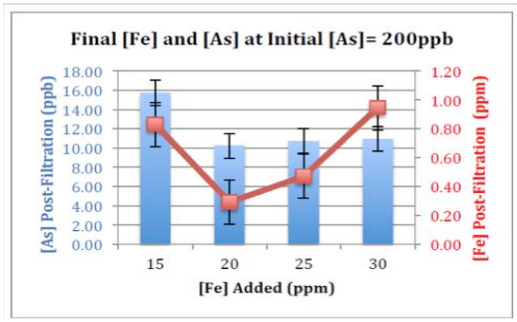


Figure B1: Final [Fe] and [As] at initial [Fe] = {15,20,25,30 ppm} & [As]=200 ppb

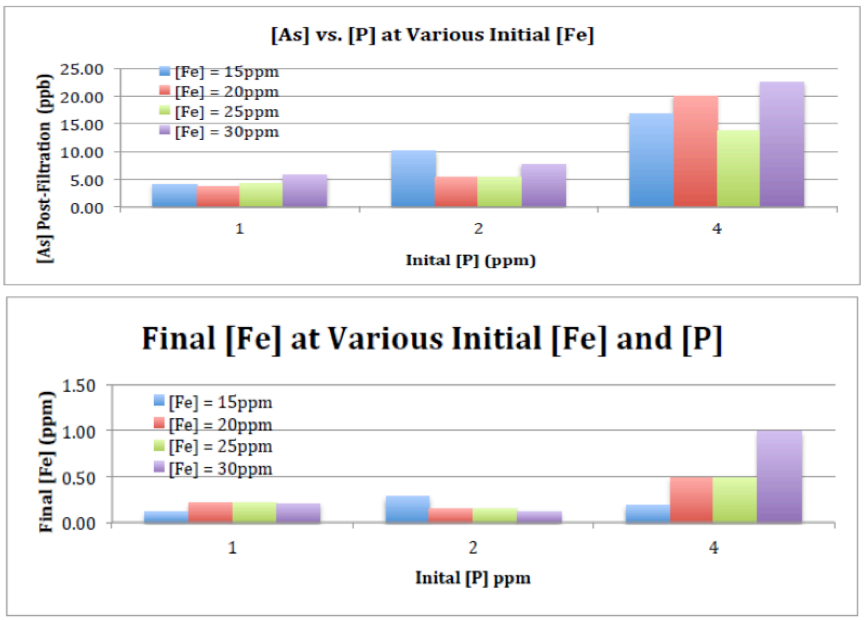


Figure B2: Final [As] at [P] = {1, 2, 4 ppm} at various initial [Fe]. Initial [As] = 200 ppm.

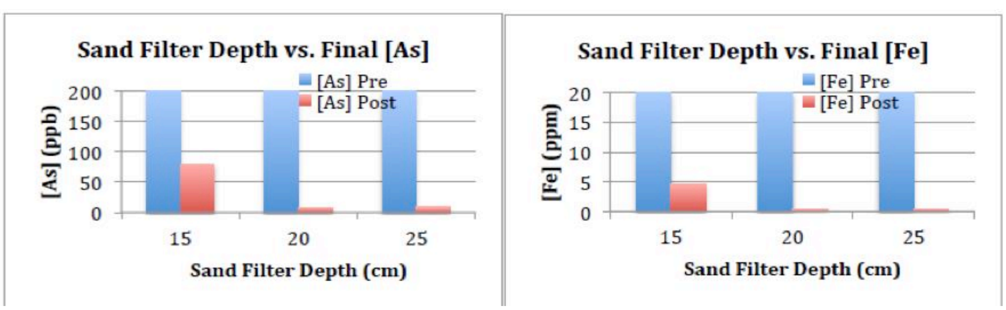


Figure B3: Comparison of effluent [Fe] & [As] at 15, 20, and 25cm filter depths. Initial [As] = 200 ppb and Initial [Fe] = 20 ppm.

Appendix C: Jeremy and Katie Skype Meeting 2/21/15

The following are notes from a video conference call on Feb 21, 2015 with Jeremy Baskin and Katie Zhang, two Dartmouth Humanitarian Engineers who spent the winter 2015 abroad in Nepal researching the current water situation and preparing for the potential distribution of the SafaPani system.

- Some Nepalese villages have overhead tanks which distribute to community taps
    - Began only 3-4 years ago but look long-term
    - Government is building 4-5 tanks per year
    - Each tank can serve 1-2 hundred households
    - Each tap serves 4-5 houses
    - Registration fee to use
    - Allowed to collect unlimited amount twice a day
    - Water from overhead tanks is “not contaminated” (50 ppb arsenic)
        - Currently being tested
    - $40,000-60,000 upfront costs supplied by:
        - 80% government and NGOs/international donors
        - 19% villagers in terms of unskilled labor
        - 1% cash from users
    - Lifespan-relatively long term
    - Wealthier have spigot nearer to their homes, live closer to highways

- Kanchan Filter
    - $75 - $100 for household filter with green pretty tiles for wealthy people
    - 5800 rupees for cheap kanchan filters
    - $4 subsidized price from NGO, entrepreneurs sell them to the NGOs
    - Looks nice, easy to clean
    - Large square shape fit well in home
    - They like the concrete. Looks more durable.
    - Put in corner, next to counter
    - 1ft by 1ft footprint of a microwave
    - 4 ft tall
    - Wealthier paid full price for Kanchan filter $76~100 unsubsidized
        - Green tile added to basic filter to make it look nicer.
        - Place in corners of kitchen (1ft x 1ft footprint x 4ft tall)
    - Proud of their filters.

- New Trunz filter on the market.
    - Sell 20L bottled water, like water coolers.
    - Pay to refill
    - Easy to buy clean water
    - Expensive to buy $60,000
- Use filtered water for drinking and cooking, but not bathing
- Daily water usage for family/household (5 people) is 20-40L.

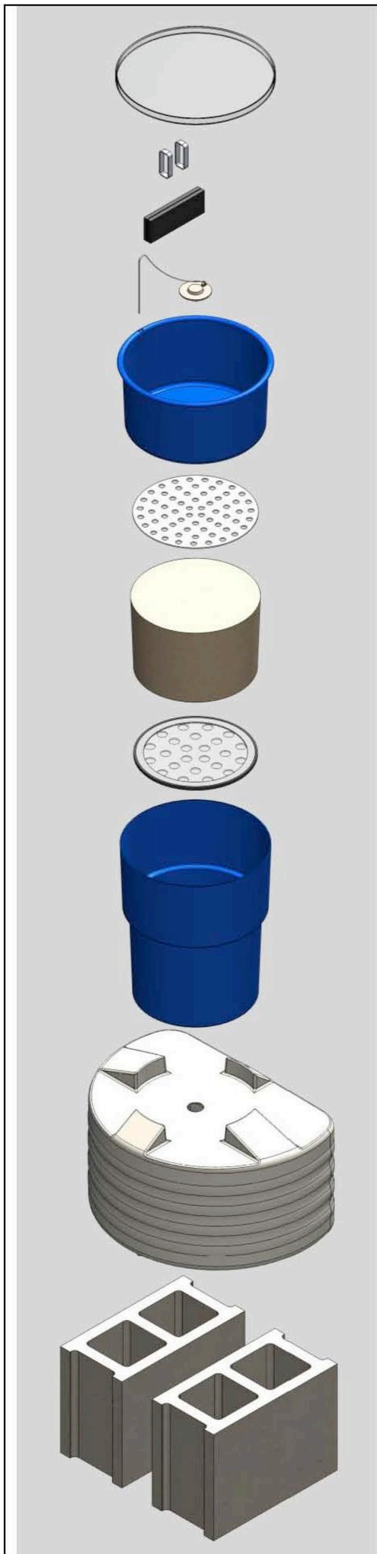
- Bath at tube well straight from well, not an issue.
- Most nepalese are farmers, welding is not a common skill.
- Cinderblocks and bricks are available and could prop up our device.
  - 1 ft off ground is fine to fill Nepalese containers
- Children aren't allowed to use the device is most cases.
  - The device is seen as too valuable to be entrusted to children.s
- Still pour water into filter whether get it from water tower or straight from well
- 12 Volt batteries are not common in households
  - Would need to buy battery, solar panels, and recharge system (which doubles cost)
  - Some Nepalese are on the grid, hence no need of battery.
    - Grid shuts off daily at known intervals for load issues, sometimes for 12 hours.
- Color preference of Katie and Jeremy. Pastel colors: Light blue, light orange, light green.

Figure C1: Water collection at a community well tap with few people lining up to fill buckets/containers.

Figure C2: Our friend Nandu standing next to a Kanchan filter that is currently being used as a planter.

Figure C3: Unused SONO filter sitting in the corner of a home in Kunuwar.

Appendix D: Detailed View of our Molded Design



Lid:	Thermoformed 0.06" polyethylene terephthalate $2.85
Electrode holders:	Cut strips of purchased Velcro Purchased plastic screws, plastic nuts, rubber washers $3.10
Electrodes:	Cut from stock iron $0.29
Flapper:	Purchased $3.00
Reaction Vessel:	Injection mold high density polyethylene $3.15
Dispersion plate:	Punch out of 1/8" high density polyethylene sheet $2.72
Sand:	Purchased $1.20
Sand screen:	Cut 1/8" high density polyethylene ring and disk Cut 1/8" rubber ring Cut nylon fabric circle Polyurethane glue $8.51
Shell:	Injection molded high density polyethylene $5.15
Reservoir tank:	Rotomolded high density polyethylene $10.00
Stand:	Purchased cinder blocks $1.50

Figure D1: Manufacturing method and cost for each component.

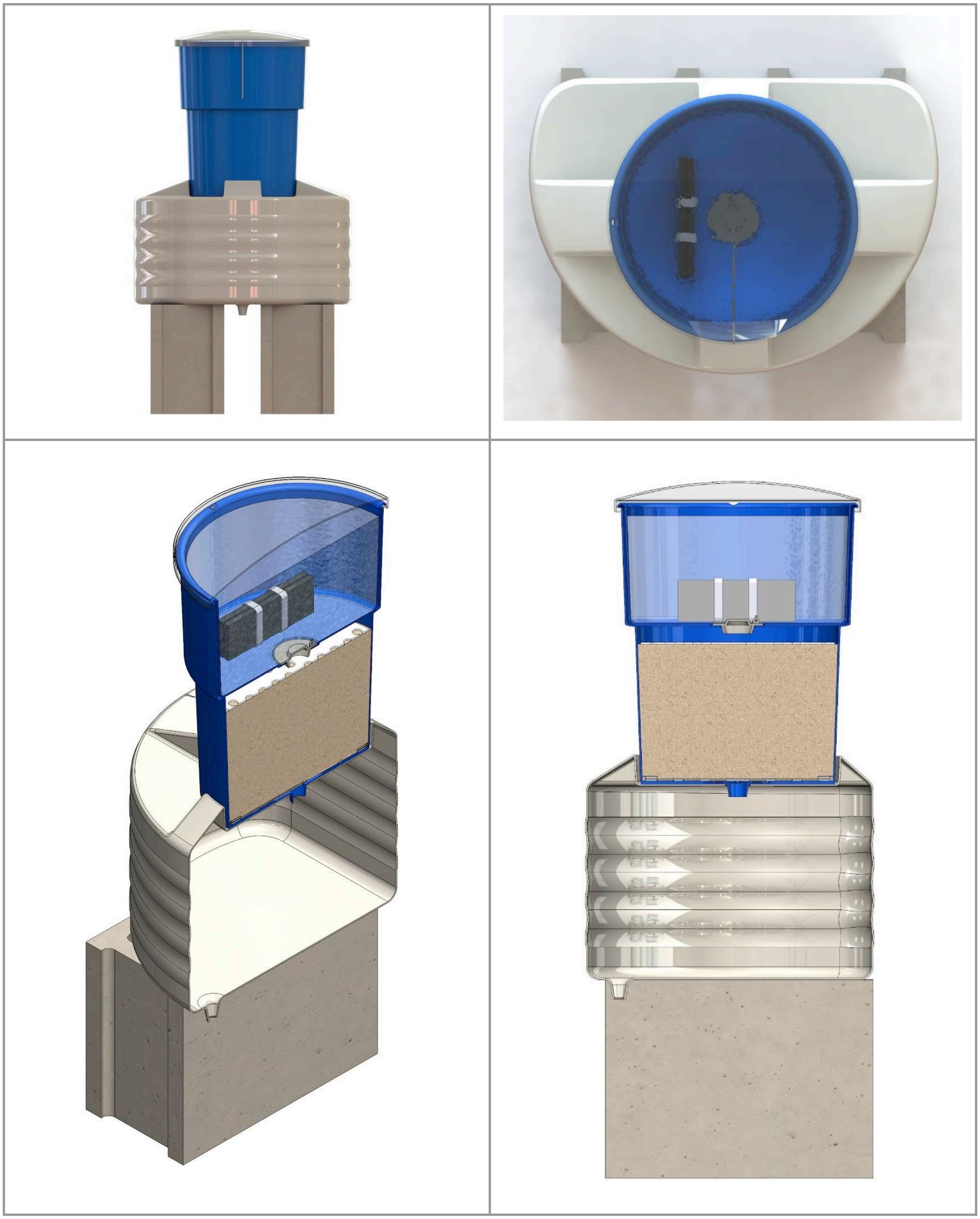


Figure D2: Detailed view of our device (Clockwise from top right): Front view, top down view, isometric cutaway view, and side cutaway view.

Figure D3: The center of mass of device without reservoir tank and stand is shown. The center of mass is on the axis in the center of the shell and in the lower half of the shell within the sand.

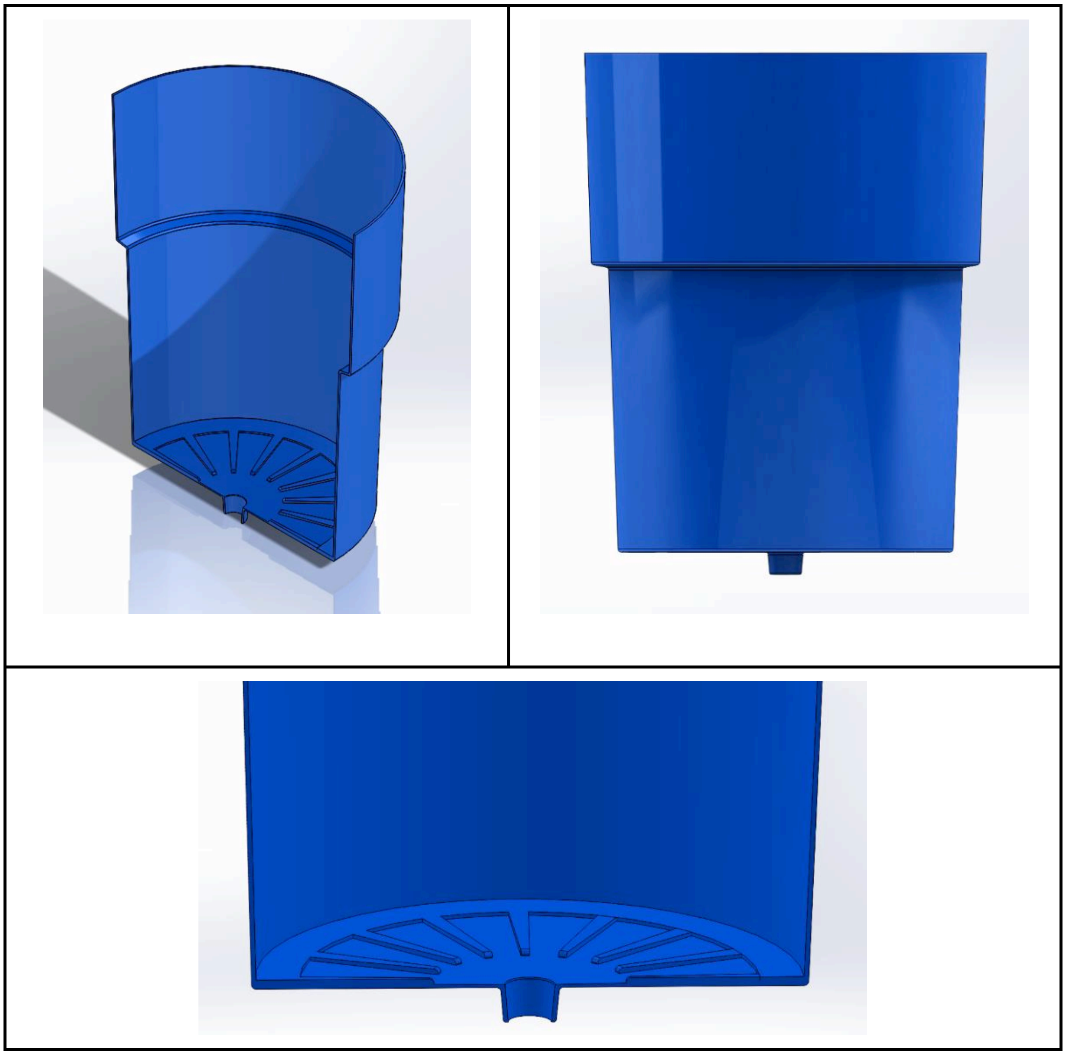


Figure D4: More detailed views of the shell (clockwise from top right): isometric cutaway view, front view, and close up cutaway view of the raised spokes on the bottom of the shell.

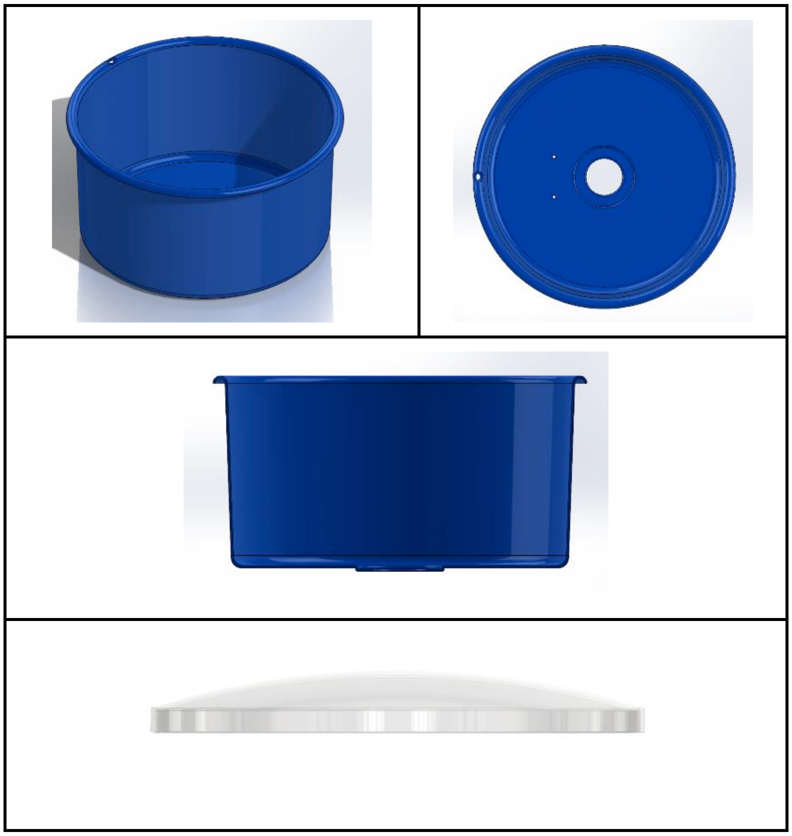


Figure D5: Detailed views of the reaction vessel (clockwise from top left): isometric view, top view, and side isometric cutaway view. Detailed side view of the lid.

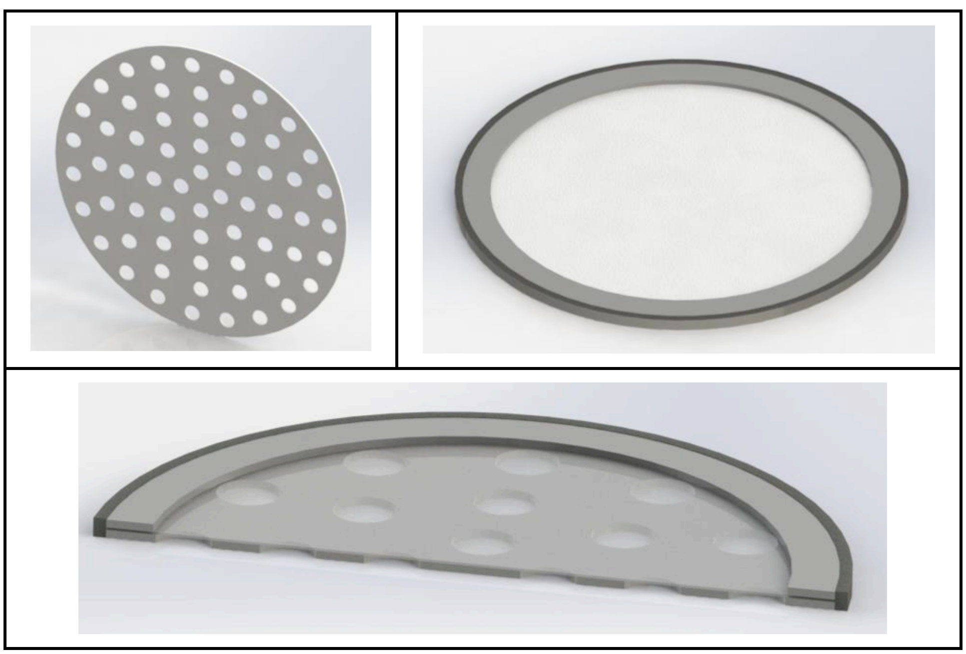
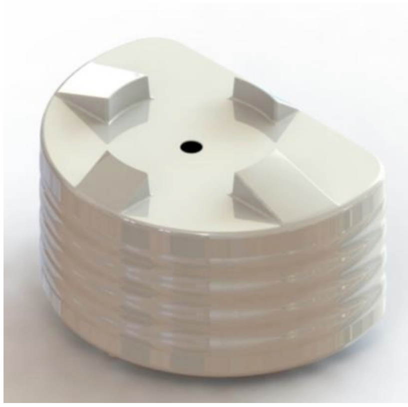


Figure D6: Detailed views of the sand screen (clockwise from top left): Sand screen support disk, Completed sand screen, Side angled isometric cutaway view.



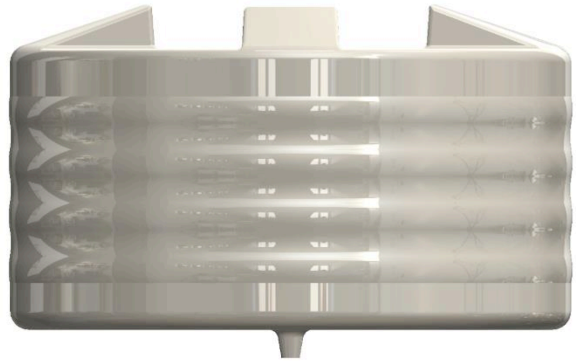


Figure D7: Isometric view and the front view of the reservoir.

Appendix E: Manufacturing and Assembly Instructions

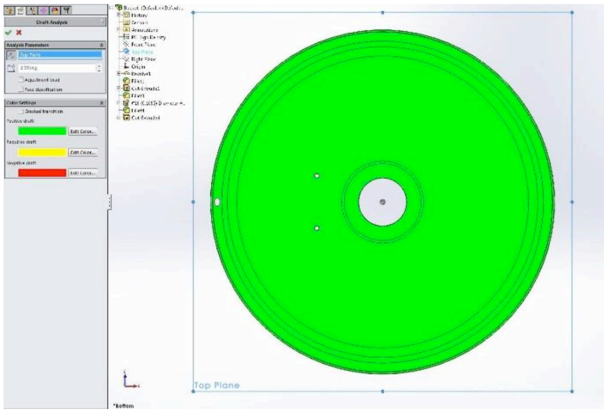


Figure E1. The reaction vessel can be molded in a 2-part mold. Draft analysis shows the reaction vessel has appropriate draft angle for molding

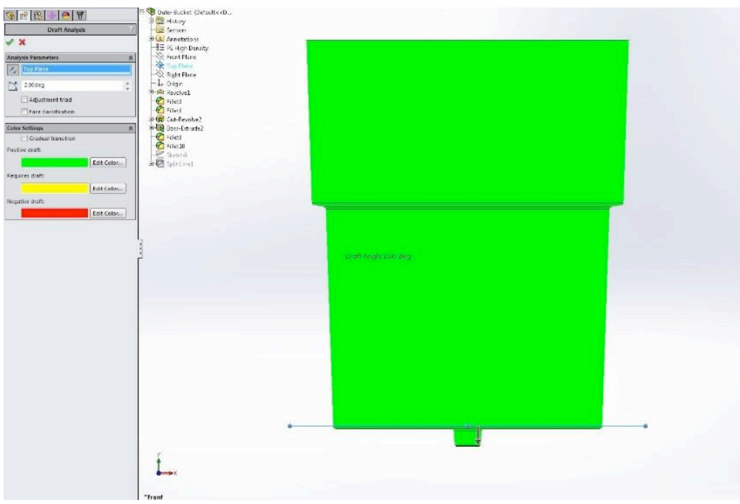


Figure E2. The shell can be molded in a 2-part mold. Draft analysis shows the shell has appropriate draft angle for molding.

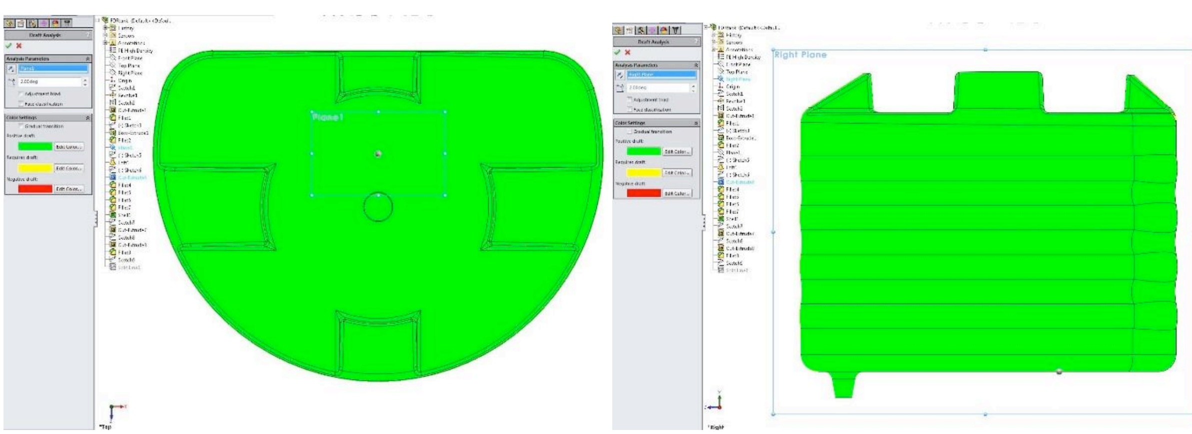


Figure E3. The reservoir tank can be molded in a 3-part mold. Draft analysis shows the tank has an appropriate draft angle for molding.

Appendix F: Manufacturing and Assembly Instructions

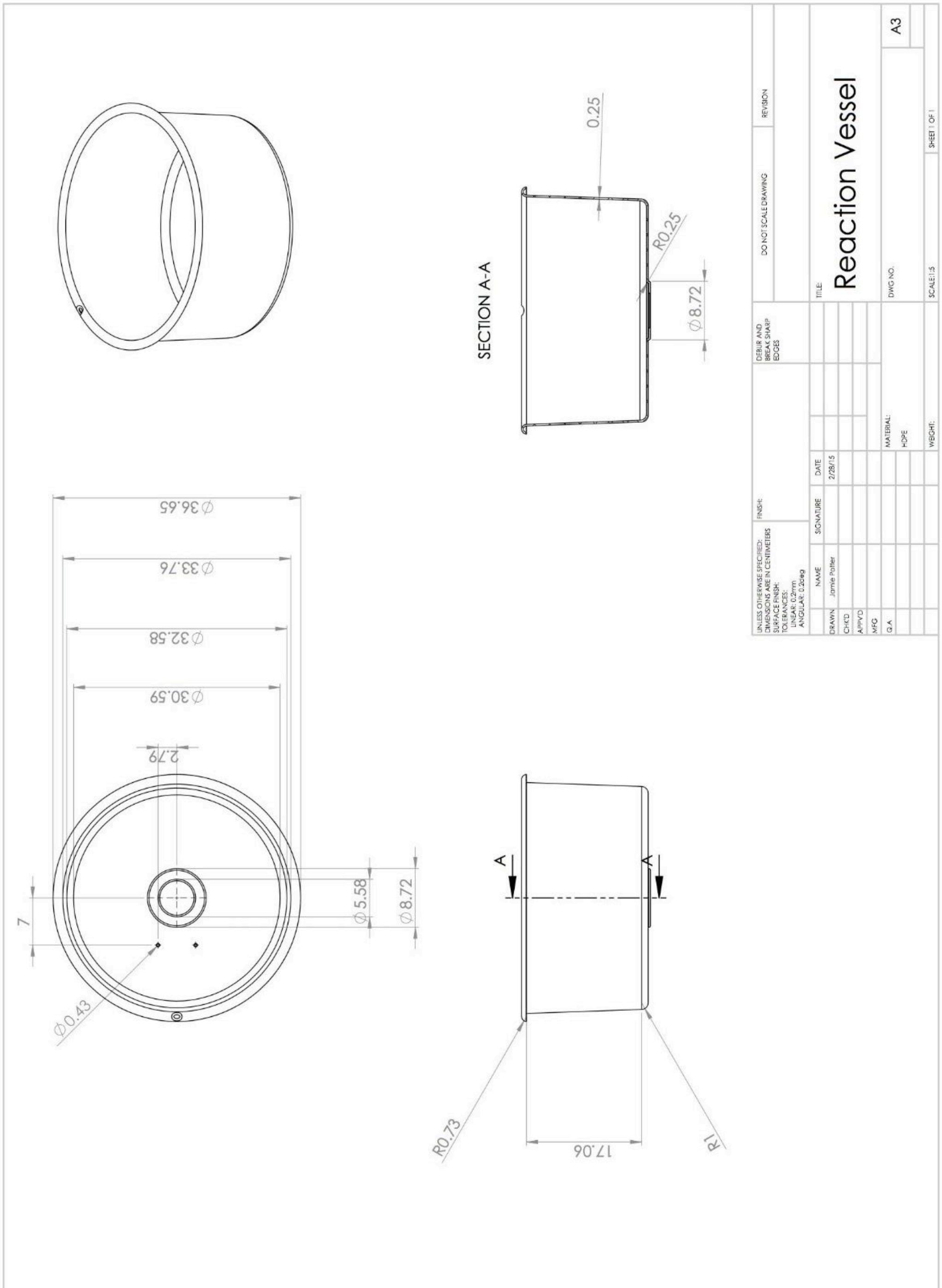


Figure F1: Engineering drawing of the reaction vessel.

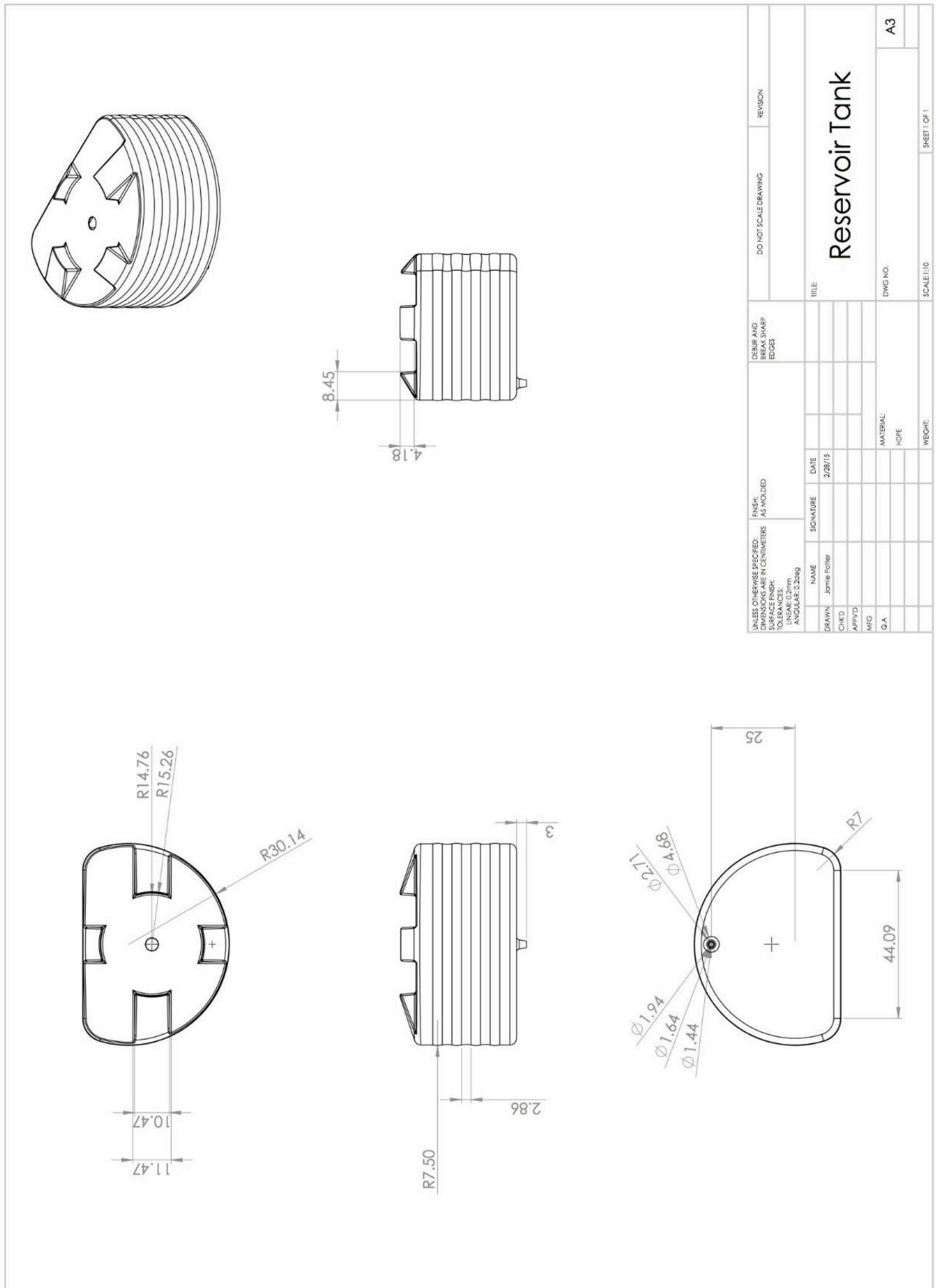


Figure F2: Engineering drawing of the reservoir tank.

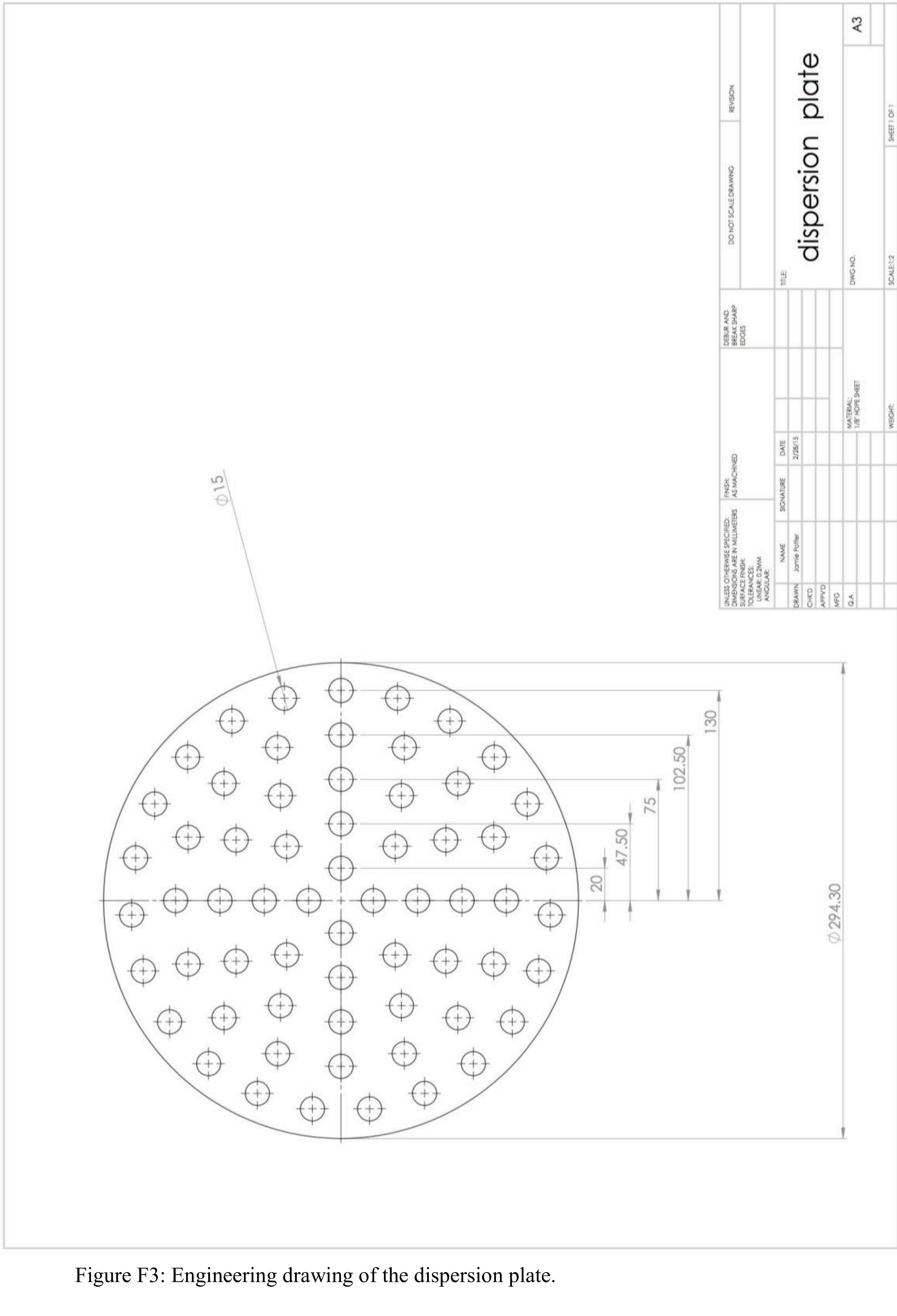


Figure F3: Engineering drawing of the dispersion plate.

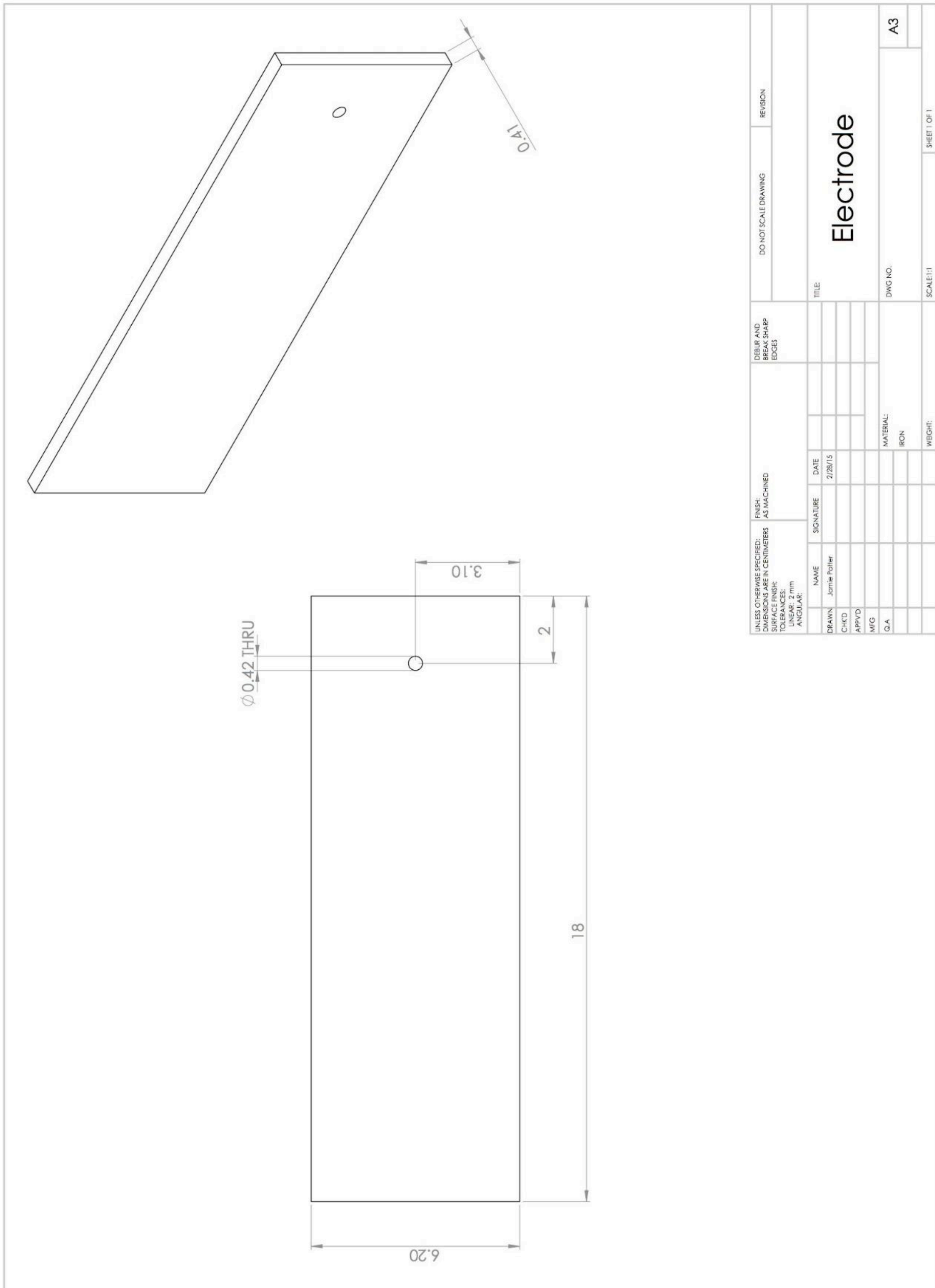


Figure F4: Engineering drawing of the electrode.

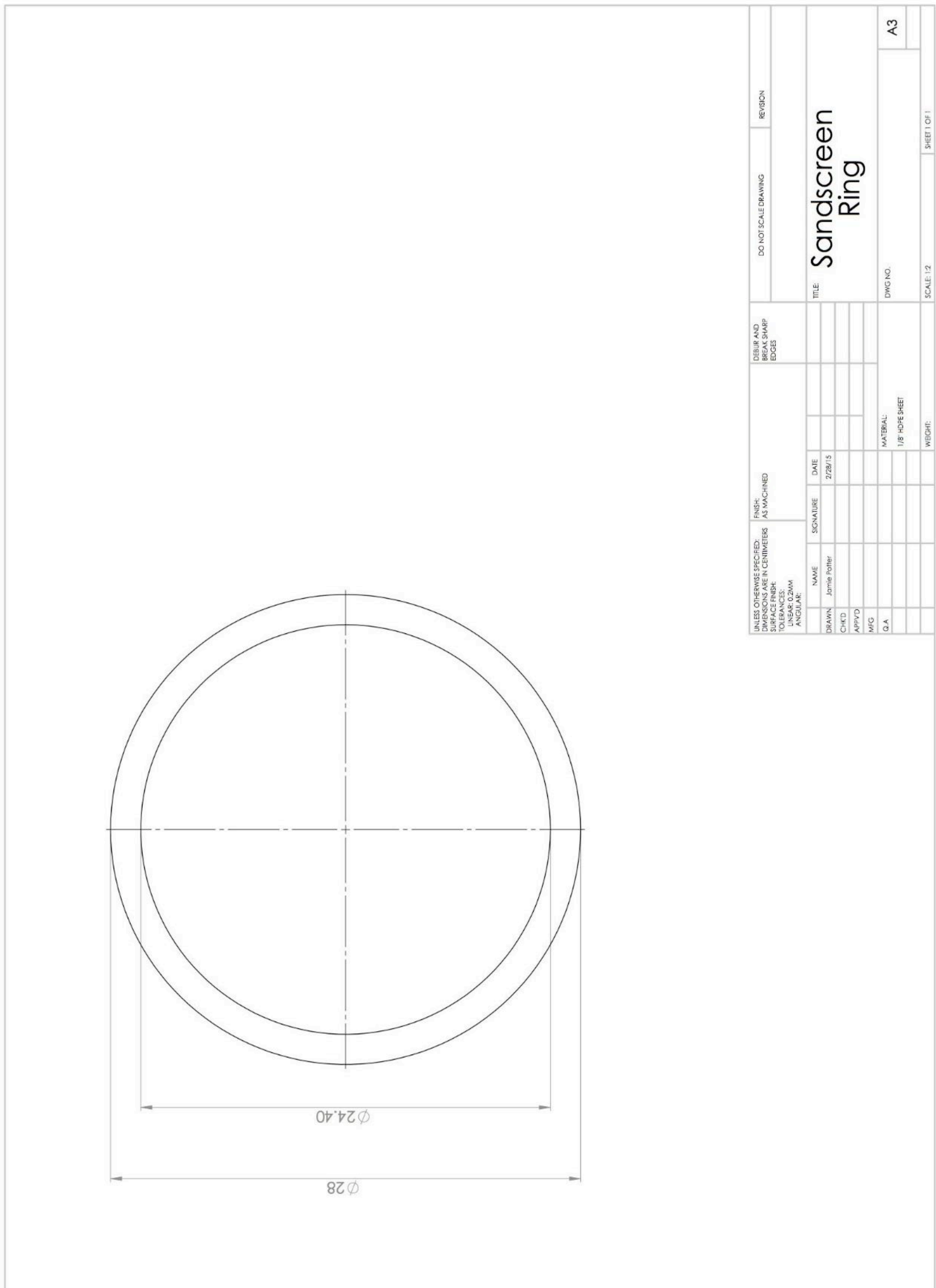


Figure F5: Engineering drawing of the sandscreen ring.

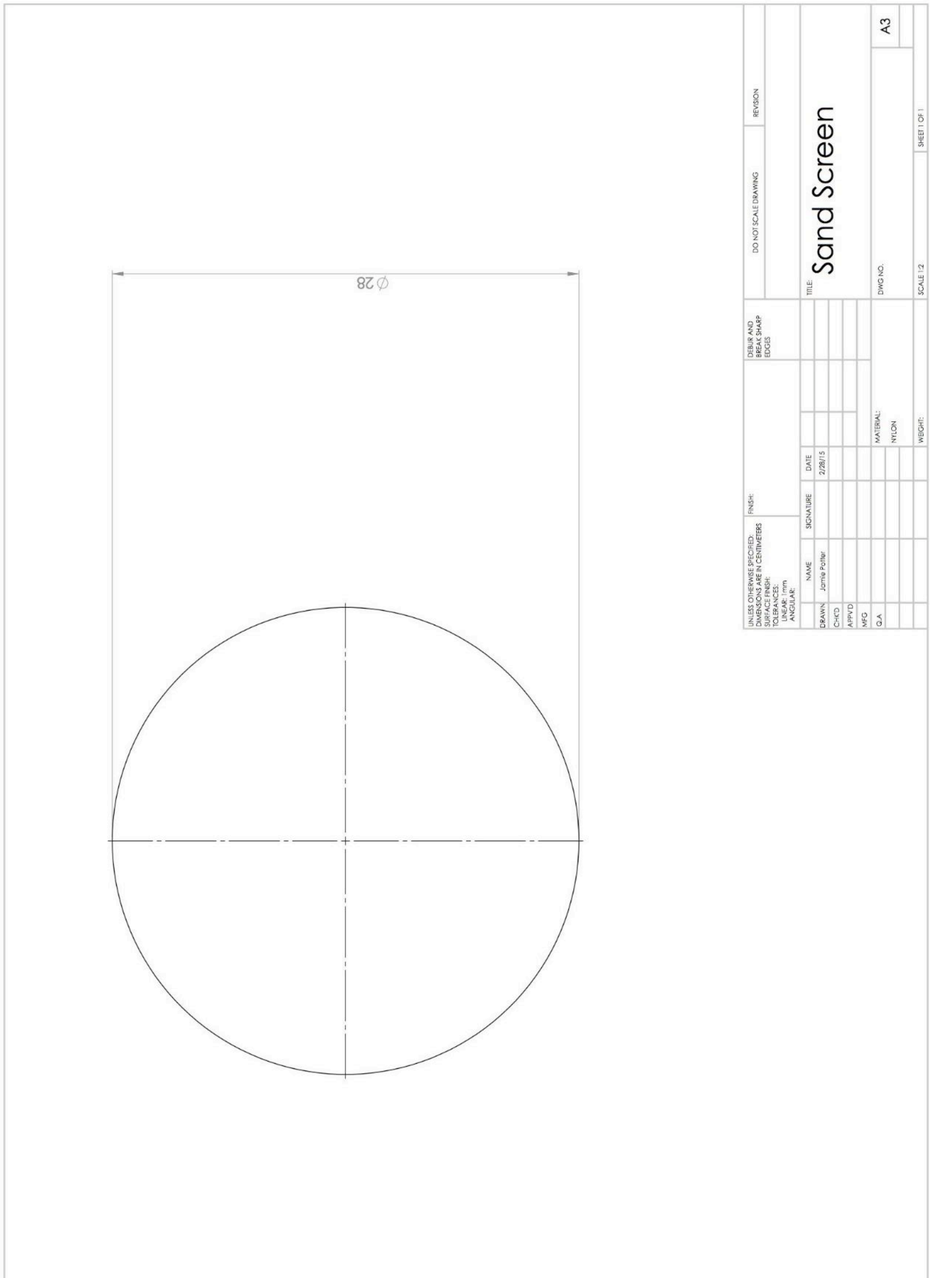


Figure F6: Engineering drawing of the sand screen.

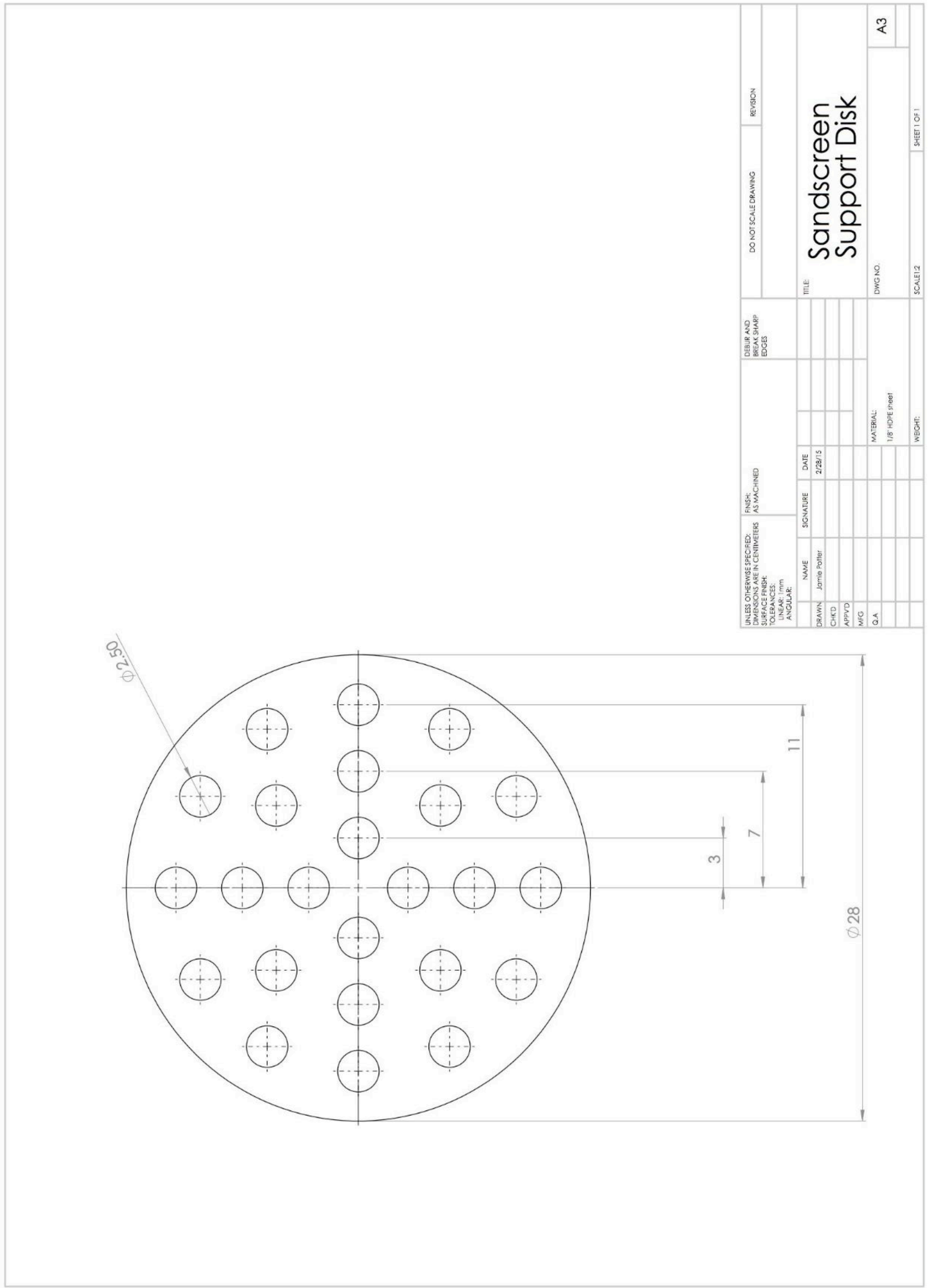


Figure F7: Engineering drawing of the sandscreen support disk.

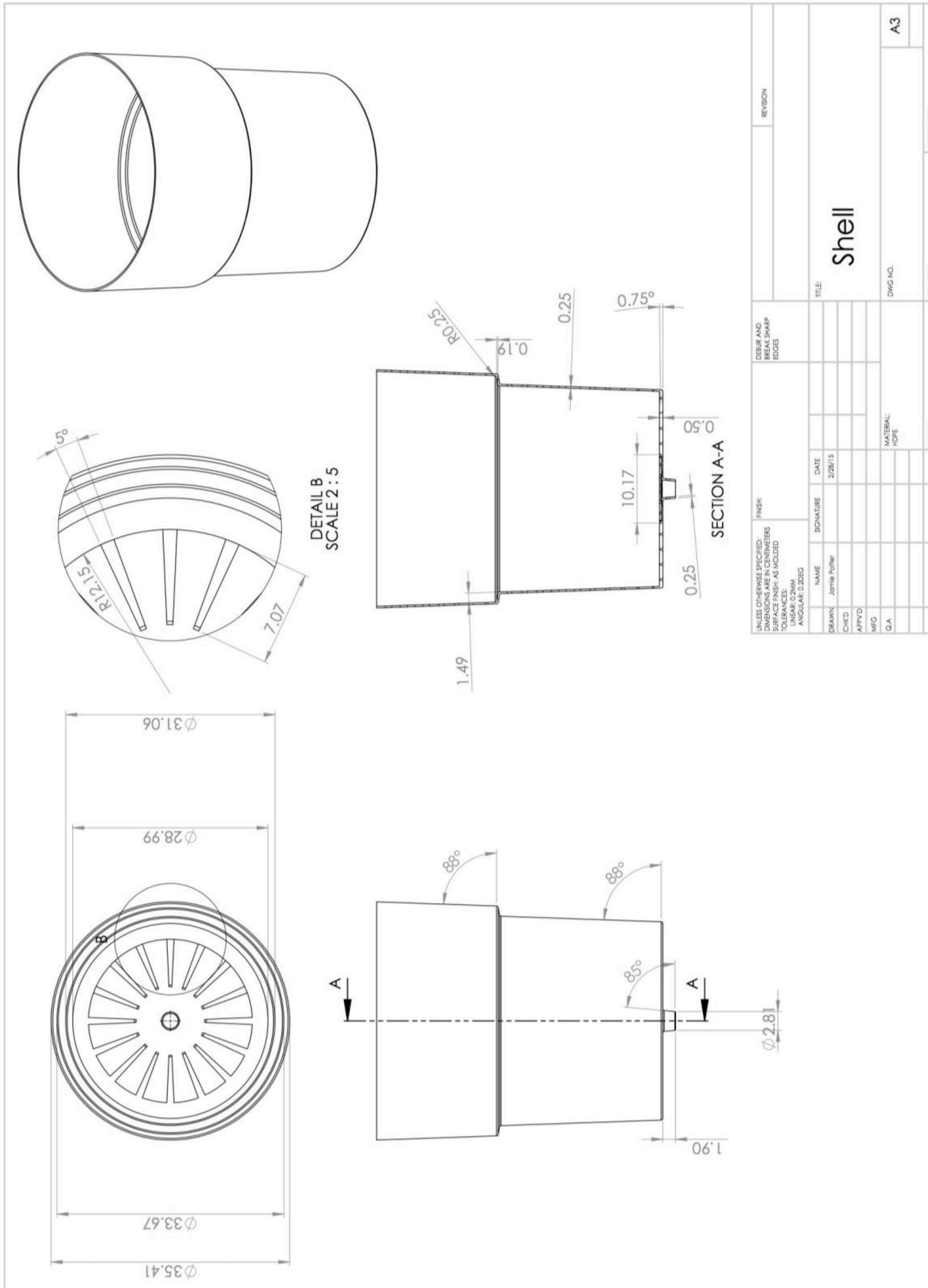


Figure F8: Engineering drawing of the shell.

Manufacturing and Assembly Instructions

1. Injection mold reaction vessel and shell, and rotomold reservoir out of high density polyethylene.
2. Pot electronics in epoxy.
3. Screw electronics board into wall of reaction vessel with nylon screws, rubber washers, and nylon nuts.
4. Insert nylon screw through rubber washer, velcro strip, and inside of reaction vessel for each of two holes. Secure with rubber washer and nylon nut on outside of reaction vessel.
5. Install flapper valve in depression in bottom of reaction vessel.
6. Connect wires to electrodes using 8-32 steel screws and nuts.
7. Place o-rings (2mm cross-sectional diameter) around individual electrodes.
8. Secure electrodes in velcro straps in upright position.
9. Place reaction vessel inside shell.
10. Place lid on top of reaction vessel.
11. Attach valve to reservoir tank spout.
12. Place tank on cinder blocks.
13. Nest shell into place on top of reservoir tank.

Appendix G: Dana Howe Meeting Notes 2/13/15

The following are notes from an onsite meeting on February 13, 2015 with Dana Howe, at GW Plastics located at 239 Pleasant Street, Bethel, Vermont 05032. Mr. Howe is a Systems manager and Cost Engineer at GW Plastics, a company that specializes in the injection molding of small complex parts for the automotive and healthcare industries. Mr. Howe showed us on the plant floor to watch the injection molding process in real time, and help give more context and understanding to the manufacturing process.

- Reaction vessel and shell should be injection molded, no considerable savings with blow molding because need inner die anyway
- Our store bought working prototype blue chemical container was injection molded
    - Text indentations incorporated into mold
    - Depressions on bottom for strength
- Reservoir needs to be blow molded or roto-molded because it's fully enclosed
- Incorporate screw holes into mold, don't drill after the fact.
- Adding threaded neck increases blow molding cost by about ~30%.
    - Blow molded bottles begin as an injection molded tube with threaded neck
- Bumps vs. Star shaped cuts in base of shell; Both accomplish increase in drainage surface area to eliminate drainage mat
- How to package and ship
    - "Expensive to ship air"
    - Make sure they nest well into each other
    - Criteria to nest: outside diameter of bottom must be smaller than inside diameter of top
- Reaction vessel flared lip will help outer shell hold its shape
- Will inject off center for reaction vessel to avoid flapper valve
    - Flow of material will be asymmetric
- Tolerance of wall thickness 2.5mm +/- 0.2mm
    - All metric units for international manufacturing
- Potential limitations:
    - Food safe approvals
    - Must validate material and once selected, very difficult to deviate
    - Reaction vessel might sink into reservoir
        - Might need to support with internal column (pipe with holes out of plastic)
- matweb.com
    - Shows regions that material is available
    - Usually not effective to import
- HDPE for reaction vessel, shell, reservoir
    - Not necessarily dimensionally stable
- Polystyrene (or polyester) for clear thermoforming
- FEA analysis to see if 80lbs can be supported by reservoir.
- Might need to increase height so that more support is directly underneath
- Add ridges for strength, they don't add too much complexity to the mold
- Draft angles no less than 2 degrees
- Stamp dispersion plate and sand screen out of a roll of polypropylene or polyethylene

- Class 6 material HDPE1245ON DOW FDA approved
    - Material pricing $1.31/lb
    - Smaller quantities for prototype $3-4/lb
- Considerations for injection molding
    - Weight of material
    - Cycle time
    - 1 cavity tool
  - 650 ton machine
    - Quality control
    - 0.25 operators per machine but would probably be higher for our pieces
    - Packaging cost: 25 cents a piece for inner bucket, 43 cents a piece for shell
- If the shell is too heavy for the tank to support, we can have a column made from a tube with holes in the sides on end placed under shell for support.
- Think of how the device might not be set level in the home, so our design must accommodate for that through the angles of our design.
- Adding a spout to the design is cheap in injection molding
- Put as much as possible of the design/manufacturing into the mold
- The changing the overall shape of the design can add more support than changing the thickness.

<u>Reaction vessel estimates</u>-per 1000 units

$2144.73-material
493.00-machine
52.17-quality control
217.00-packaging
\+ 46.58-die maintenance

$3144.63 or about $3 per piece (excluding mold)
$17,000 for mold

<u>Shell estimates</u> (with similar break down)
$5152.38 or about $5 per piece
$22-24,000 for mold

Appendix H: Rotomolded Tank from Calcutta

Figure H1: Example rotomolded water tank in Calcutta. (Image courtesy of Jaydeep Dasgupta)

Appendix I: Failure Modes and Effects Analysis (FMEA) and Safety Risk Assessment (SRA)

FMEA Analysis							
Failure Mode	Effects	Cause	Control Method	SCORES			Total
				SEVERITY	LIKELIHOOD	CONTROL	RPN SCORE
Falls over	-Breaks device shell or reaction vessel -Dents device shell or reaction vessel -Dislodges wires in circuit	-Cinderblock fails -Deformation of device shell -Device is bumped or nudged	-Device shell is seated in the reservoir	4	2	3	24
Plastic fatigue	-Breaks device shell -Warps device mold	-Load over time	-Thick walled design -Additional support added to design	4	3	1	12
Lid breaks	-Debris enters reaction vessel -Biological pathogens enter reaction vessel	-Device falls over -Heavy load placed on lid and	-Domed shape to prevent object resting places -Strength built into lid deign	3	2	1	6
Flapper seal breaks/clogs	-Contaminated water leaks into sand filter -Clean water cannot flush into sand filter	-Iron particulates build up in reaction vessel -Seal is not clean	-Flapper and seal are replaceable in case of wear	4	3	2	24
Electrode short	-Fries circuit -Electrocutes user	-Iron particulates build up between electrodes	-Exposed wire is minimized and properly fixed -Reaction vessel is cleaned regularly	5	2	2	20
Sand screen breaks	-Sand enters reservoir, contaminating sand -Sand clogs outlet valve	-Weight of sand causes adhesion failure -Fabric is punctured when sand is being changed	-Nylon fabric is supported by sand screen disk -Nylon fabric is strong	3	4	3	36
Wire connections break	-Electrocoagulation does not occur, arsenic still in water	-Wires are under wear over time or pulled	-Wires are secured on each end	3	2	1	6
Plug in backwards	-Circuit is damaged and will no longer work	-Can be connected to the battery in either direction	-Can only plug into battery one way due to geometry of plug -Schottky diode placed in series with circuit device	5	2	1	10
Faucet breaks	-Water continuously flows out of device	-Sheared off -Part breaks	-Faucet is inset to avoid being hit	4	2	2	16
Sand channeling	-Minimum height of sand filter is not met	-Continuous flow in one part of the sand	-Incorporated dispersion plate to disperse the water over the whole surface area of the sand	3	4	1	12
Spill bad H2O on reservoir	-Unclean water enters the reservoir, bypassing the filter	-Accidental spilling while filling the device -Various kitchen spills	-Added a lip on the top of the reservoir to shed water off the device instead of into the reservoir	3	2	2	12
Spill something on lid	-Unclean water enters the reaction vessel at the wrong time	-Accidental spilling while filling the device. -Various kitchen spills	-Added flange to the reaction bucket, so the lid will shed spills off the device onto the reservoir.	2	4	1	8
Turn on W/o water	-12V of charge would build up on electrodes	-User forgets to refill reaction vessel before hitting switch -User accidentally bumps switch on	-Current sensor will sense zero and the green LED will not light, indicating incomplete reaction	2	1	1	2
Flapper open when water poured in	-Arsenic passes through sand into clean reservoir -User ingests arsenic	-User forgets to release flapper chain before refilling reaction vessel	-Affix clip for flapper chain to lid, such that the user cannot remove the lid without releasing the chain and closing the flapper	3	4	3	36
Arsenic build up	-System gets overloaded with too much arsenic to chemically react with, and lines the sand filter with arsenic residue -User ingests arsenic	-Sand is not scarified/replaced frequently enough -Electronics fail -Arsenic concentration too large for system to handle	-Advise monthly cleaning/maintenance regimen -LED indicator if electronics have low battery or other issue -Optimize electrocoagulation time to deal with high concentrations	5	2	2	20

Table I1: FEMA analysis results.

SRA Analysis									
Function	Failure Modes	Assumptions	Hazard	Frequency	Likelyhood	Severity	Total	Risk Level	Risk Reduction Plan
Provide power	Injury due to misuse of device	Device will be mounted on cinderblocks to provide a level surface	Electrocution	5	1	3	15	Acceptable	-Design plug/connection to be used in one direction only -Design automatic shut off if no current is sensed
Device stands upright	Device is knocked over onto person		Impact or crush injury	2	1	1	2	Acceptable	-Design will minimize center of mass to provide maximum stability
Remove arsenic	Contaminated water gets into reservoir	Device will be operated following given instruction manual	Arsenic ingestion	5	2	3	30	Actionable	-Design will promote water shedding -Design will facilitate closing of flapper valve to seal off contaminated water -Suggest regular cleaning of the device
Maintenance	Injury due to heavy lifting	Sand will be scooped out in small increments	Strain injury	2	1	1	2	Actionable	-Maximum weight of sand is manageable

Table I2: SRA analysis results.

Appendix J: Fabric Testing Protocol and Results

Mesh/Fabric Testing Protocol

Procedure:

1. Cut a 14” diameter circle out of each fabric to be tested
2. Place one piece of fabric into ~1.5 gallon bucket (should bunch and look like a coffee filter)
3. Pour 750g of (Home Depot play sand) sand into the bucket with filter
4. Pour 1 L of water through the sand (this step is to saturate the sand with water)
5. Allow water to run through until all water has run through and sand is saturated
6. Pour 1 L of water into bucket and begin timer at first contact of stream with sand
7. Stop timer when drips of water are 5 seconds apart

	Fabric Testing						
	Cotton	Polyester	Polyester-Cotton	Nylon	Agricultural	Weed-Blocker	Solar Screen
Lets sand through?	No	No	No	No	No	No	Yes
Lets water through?	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Flow rate (L/s)	0.0400	0.0250	0.0263	0.0313	0.0200	0.0357	N/A

Table J1: This table summarizes the results of the fabric testing. Because of its fast flow rate and durability, nylon was chosen as the optimal fabric.

Appendix K: User Testing Results and Questionnaire

User Questionnaire

Subject name______________ Date and time of test______________

1. How easy were the electrodes easy to replace? (Circle one, 1 not at all, 5 very)

1 2 3 4 5

2. Was the sand easy to access?

1 2 3 4 5

3. Was the device intuitive to use?

1 2 3 4 5

4. Was the device easy to use?

1 2 3 4 5

5. How helpful was the instructional guide?

1 2 3 4 5

Name one way in which you would improve this device.

____

For Group 15 only:

Time to change electrodes_________

Overall running time for device_________

Figure K1: This figure shows the questionnaire given to test subjects upon completion of testing. The questions seek to determine both how intuitive our device is to use and how to improve on the design.

User Testing										
Subject Name	Date of Test	Time of Test	Electrode Change Time	Flowrate (L/min)	Q1	Q2	Q3	Q4	Q5	Improvement Suggestion
Lorin P.	2/26/2015	10:30 AM	1:00 min	0.711	5	4	3.5	5	3	Include step stool with device
Brock	2/26/2015	10:55 AM	1:45 mins	0.732	4	4	3	3	3	Labels or color coding for operating device
Max H.	2/26/2015	11:35 AM	1:36 mins	0.723	4	5	4	5	5	Include a fill line in reaction vessel
Jacob M.	2/26/2015	12:45 PM	1:32 mins	0.723	4	5	4	5	5	Use stop sign or clock instead of hand for 'wait' symbol
John S.	2/26/2015	1:30 PM	1:05 mins	0.687	3	3	3	4	5	Clearer instructions for operating device
Ben P.	2/26/2015	2:43 PM	58 secs	0.613	3	4	2	3	3	Include instructions for replacing electrodes
Malia K.	2/26/2015	3:22 PM	1:04 mins	0.645	4	4	3	4	2	Pull cord and wires coming out of bucket should not get tangled
Bryan R.	2/26/2015	3:40 PM	1:52 mins	0.657	3	4	4	4	4	Include picture of what correct electrode setup should look like
Nicole S.	2/26/2015	4:05 PM	1:35 mins	0.644	4	2	3	3	4	Include picture of closed flapper valve in instruction
Byoung J.	2/26/2015	8:58 PM	N/A	0.625	1	4	3	4	5	Include instructions for replacing electrodes
Laura V.	2/26/2015	10:09 PM	1:26 mins	0.671	4.5	3	3.5	4.5	3.5	Include label on places to pull and cartoon-y instructions for use
			Average	0.676	3.6	3.8	3.3	4.0	3.9	

Table K1: This table summarizes the data obtained through user testing.

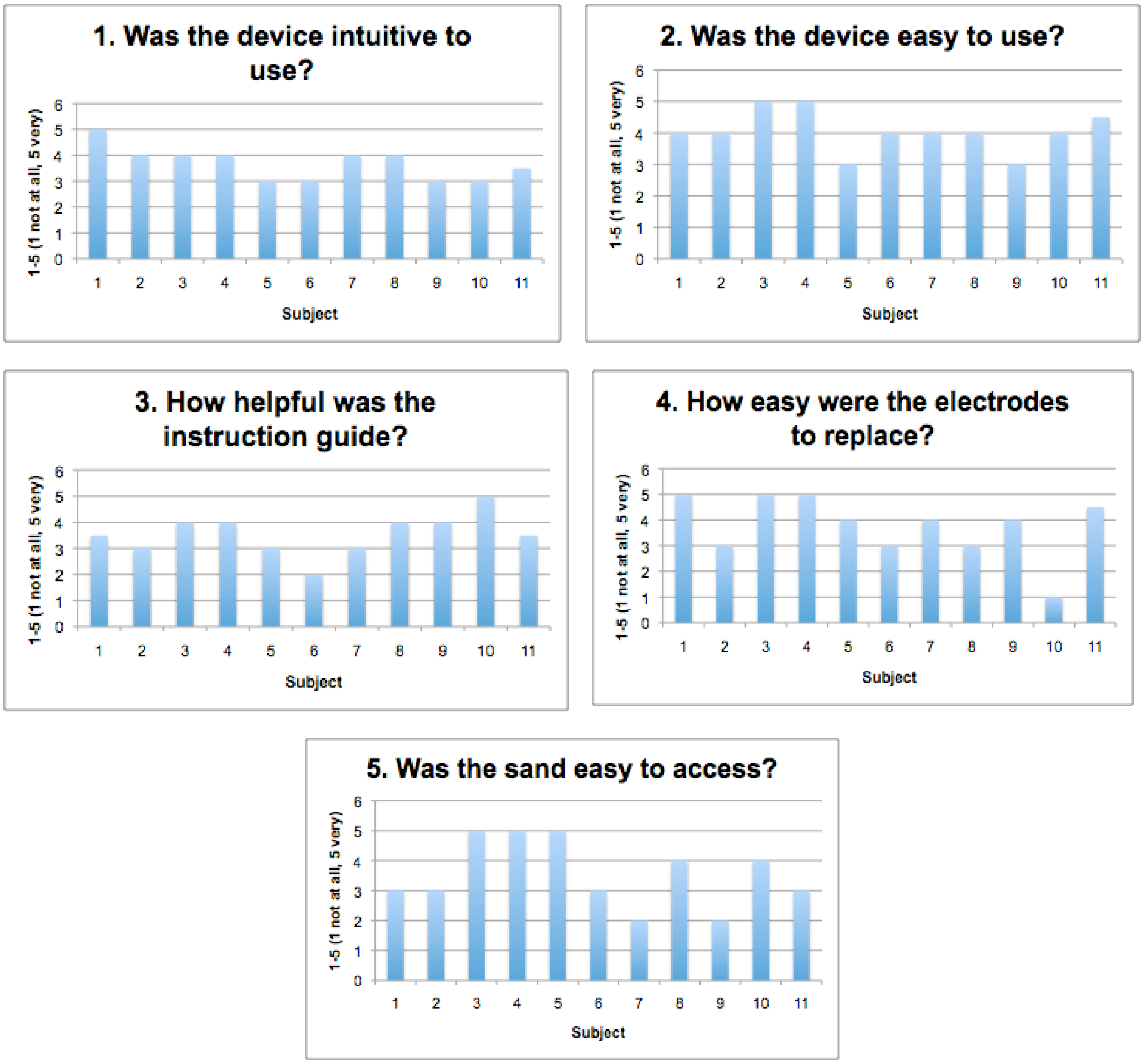


Figure K2: These five graphs show the ranked (on a 1-5 scale) responses of users to each of our five survey questions.

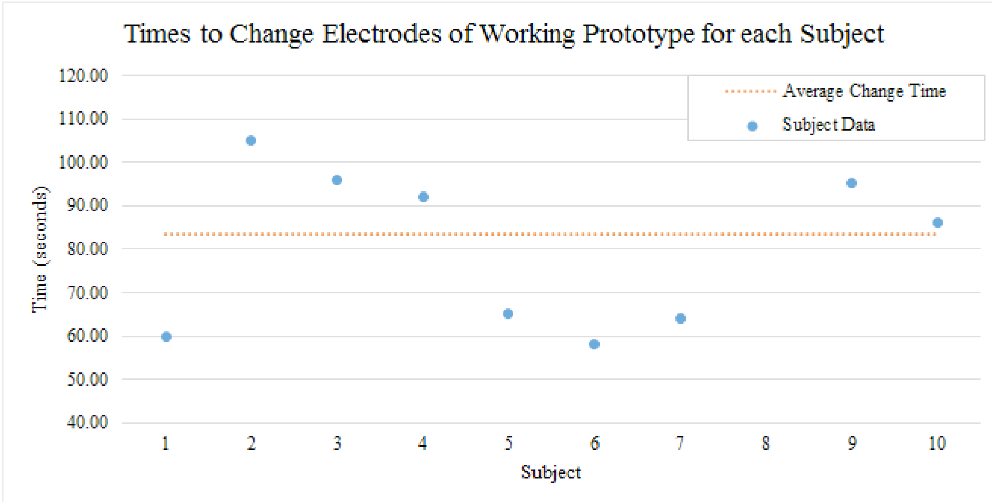


Figure K3: Times for each subject to replace electrodes plotted with a line showing the average time to change electrodes over all testing.

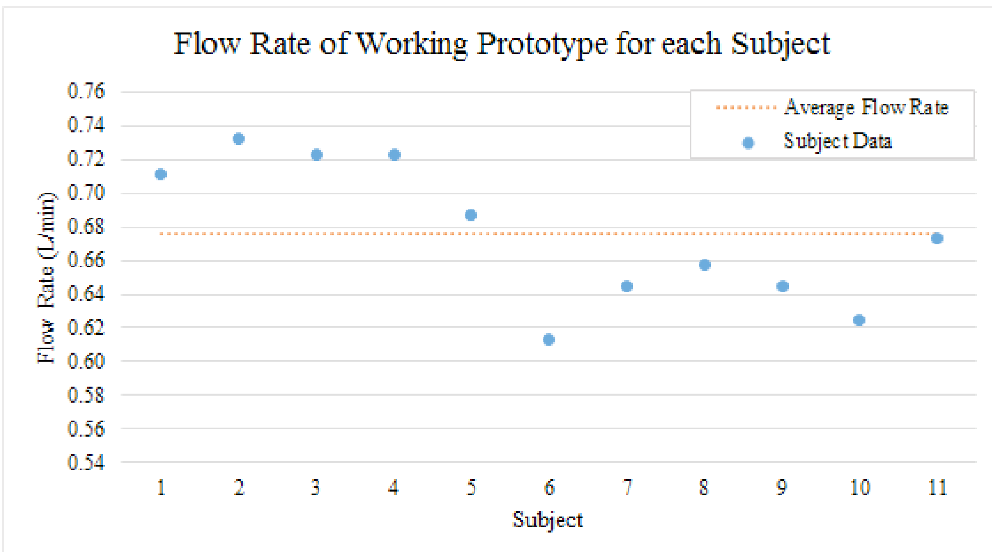


Figure K4: Flow rate for each individual test subject plotted with the average flow rate over all testing.

Appendix L: Pictorial Instruction Guide and Steps to Perform

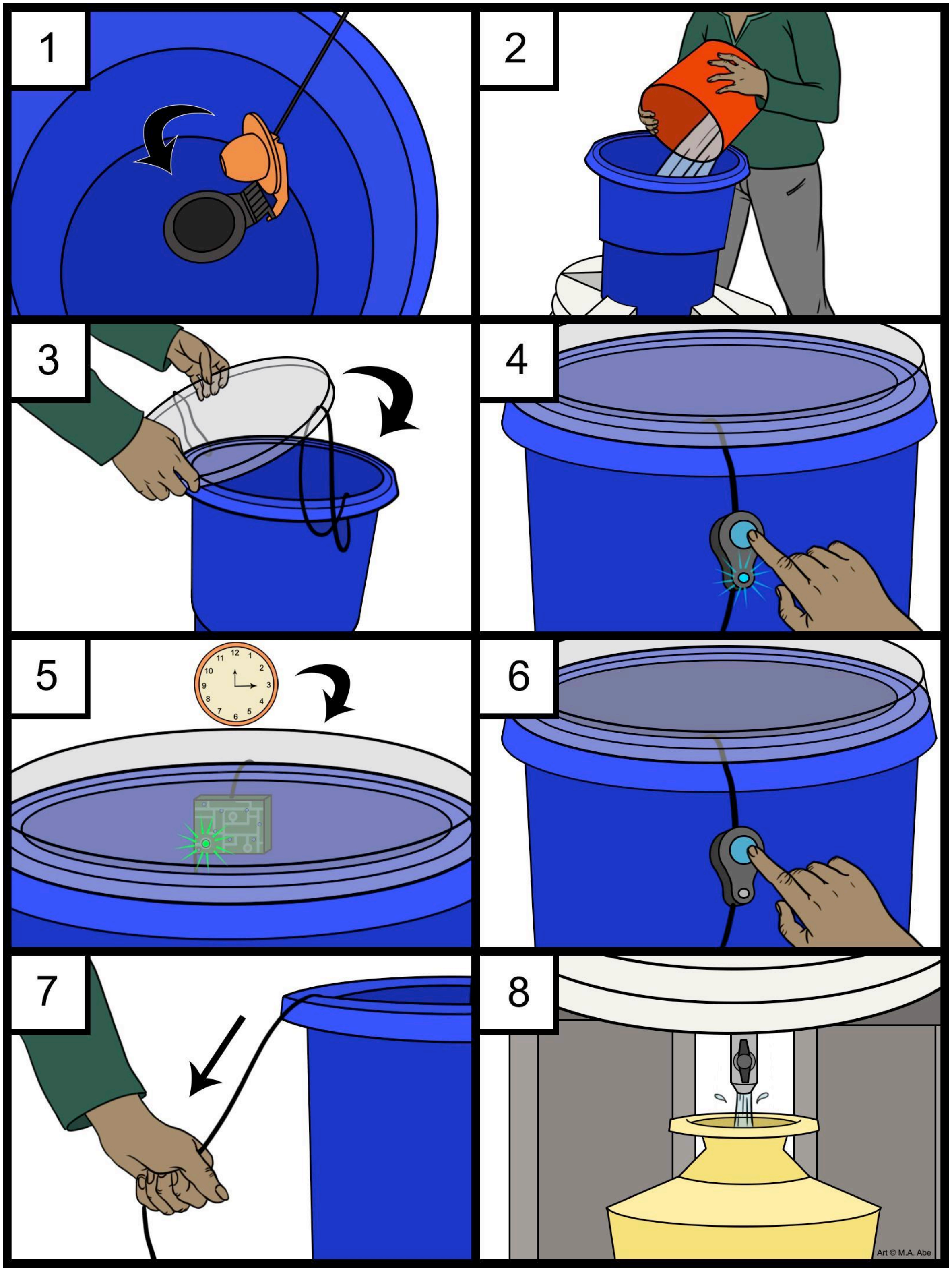


Figure L1: Pictorial guide for use of the SafaPani.

The steps in words are as follows:

1. Close flapper valve
2. Pour in water
3. Close lid
4. Switch on
5. Wait
6. Green light will turn on
7. Pull cord and hook it to wall of outer bucket
8. Switch off and open tank valve

Appendix M: Detailed Electronics Description and Parts List

SafaPani Controller Circuit Manual

High Level Requirement

The controller circuit controls the current through the electrodes submerged in the reaction vessel, and uses LEDs to communicate its internal state to the user. Charge through the electrodes will be monitored by measuring the current in the circuit at equal time intervals, and then performing discrete integration of current with respect to time. The outputs from the LEDs are as follows:

Green: Turn ON when mixing time is over. OK to open valve to sand filter.
Yellow: Slow blink when the electrodes are powered. Fast blink during mixing time.
Red: Blink for low battery.

The power source will be a 12 volt deep cycle battery. When the battery approaches the minimum voltage range, the Red LED will blink to signal the user. The controller will go to sleep if the battery gets past this minimum voltage. The controller will be turned on and off with a switch placed in series with the power wires.
<<NOTE: user testing and focus group input is needed to refine the blinking and on/off sequence of the LEDs, to be sure that they clearly indicate to a non-expert user, in another culture, what is happening.>>

Implementation Requirements

An 8-bit microcontroller will be used as the brain of the circuit. Since the electrolytic load will be variable, the microcontroller will control the current with logic-level MOSFET. If a Stirrer is added in the future to increase mixing efficiency, it will also be controlled with a second MOSFET.

To measure charge passed to the water, we will monitor the current in the circuit. To check if the battery is approaching its lower limit, we will need to monitor the source voltage.
The microcontroller uses a reference voltage to convert an analog signal to a 10-bit digital value. To perform accurate voltage and current measurement, we need to have a constant voltage source. However, the battery we will be using can vary from 13.5 – 11.0 volts during its operation cycle. For this reason, we will also need to include a voltage regulator that provides a lower constant output voltage regardless of source voltage. The choice of voltage regulator also depends on operational voltage of microcontroller.

Summary of Inputs to the Controller:

- Battery voltage reading
- Electrolytic current reading
- Summary of output signals from the Controller:
- Red LED
- Green LED
- Yellow LED
- MOSFET to control electrolysis
- MOSFET to control stirring [note: stirring may not be a feature of the first designs, but the electronics should be designed to accommodate stirring in future versions, if needed.

Process Flow

The flowchart in figure K1 describes the method used by the microcontroller to oversee the electrolysis process. The circuit periodically checks the battery voltage and shuts off the electrolysis process if the battery is too low. It also checks the current and updates the total charge that has crossed the electrodes. This value is proportional to the amount of iron ions released into the water, and is used as a measure to end the electrolysis process. After this charge limit is reached, the controller simply waits for a specified amount of time to let the iron ions react with the arsenic.
<<NOTE: Testing is needed to determine the amount of charge and the mixing time necessary to react with common arsenic levels seen in Nepal.>>

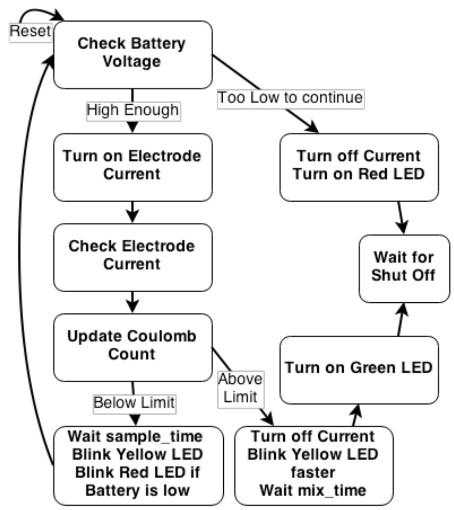


Figure M1: SafaPani microprocessor flowchart showing the steps used to control the electrolysis process.

Circuit Description

Microcontroller

The controller will need to control three LEDs, take current and voltage measurements, and control current to the electrolysis process via a logic-level MOSFET. We had initially thought of using ATtiny 85 for the project because of its tiny form factor and low cost. However, the ATtiny85 has only 6 usable IO pins and we will need at least 4 output pins and 3 input pins. For development and testing purpose, we will also need to have enough memory on chip to collect field data for later analysis. Therefore it would be best to use a development platform like Arduino Nano for development platform and use a bigger microcontroller like ATtiny84 for the wide scale production device.

Here are the features of Arduino Nano and ATtiny84 that will be most important to our project:

Arduino Nano:

- Has inbuilt voltage regulator which will make early development process easier.
- Input Voltage limits 7-12 volts.
- Operation logic level voltage: 5
- Analog Input pins: 8
- Digital I/O pins: 14

- Analog to Digital Converter: 10 bits
- 32 KB of flash memory useful for logging data
- USB port of power data stream. <<Note: voltage from USB might be unreliable.>>

ATtiny84:

- $1.50
- 8 KB of non-volatile FLASH memory for code
- 512B EEPROM for non-volatile data
- 512 B SRAM for run-time data
- Programmable in Arduino Environment
- Input Voltage: 2.7 – 5.5V
- Analog Input pins:
- Digital I/O pins:
- ADC channels: 8 at 10 bits
- Timers: 2-
- Has sleep functionality with significantly reduced power consumption.
- Analog to Digital converter: 10 bits

ATtiny85:

- $xxx
- 8 KB of non-volatile FLASH memory for code
- 512B EEPROM for non-volatile data
- 512 B SRAM for run-time data
- Programmable in Arduino Environment
- Input Voltage: 1.8 – 5.5V
- Analog Input pins + Digital I/O pins: 6
- ADC channels: 4
- Timers: 2
- Has sleep functionality with significantly reduced power consumption.
- Analog to Digital converter: 4 at 10 bits
- 8 KB of flash memory for program

Current Measuring

Initially we had planned to measure the current by measuring the voltage drop across a known resistor value. However, this wastes a significant amount of energy through heat. For example, the AD converter has only 10 bits and the voltage resolution would be about 5mv/unit. If we use a 0.1 ohm resistor, the current resolution would be 50 mA/unit which is insufficient to perform proper charge calculation.

For this reason, we decided to use a MAX4080 current sense amplifier. The SAUS MAX4080 chip measures voltage drops across a shunt resistor (0.05 Ohms) and magnifies that value by a gain of 60. More information about the current sense amplifier can be found from the link (datasheets.maximintegrated.com/en/ds/MAX4080-MAX4081.pdf)

Voltage Measuring

Voltage Measurement is done using a simple voltage divider with two resistors in parallel to the circuit, and therefore power consumption will be of not a great concern. The resistors, 22.1k and 10k, drop the maximum battery voltage of 12V down to 3.74V, a value that can be read by the ATtiny84's ADC.

Voltage Supply to Microcontroller

The circuit is powered with a 12 Volt deep cycle battery. However, the ATtiny84 microprocessor requires a 5 Volt power supply. Therefore, a 7805 Voltage regulator is used to supply 5 Volts to the microcontroller.

In System Programmer

In order to manufacture thousands of these circuits, a simple and robust method of programming the ATtiny84 is required. A dual inline 6-pin header is soldered to the PCB to allow an AVRISP MKii device to quickly program the ATtiny84, and the circuit is designed in such a way that in-system programming is possible.

Circuit Schematic and Board Layout

The individual pieces described above have been synthesized into the circuit schematic shown in figure L2. The figure shows a high-level diagram of the circuit with its individual components, as well as a detailed Eagle schematic.

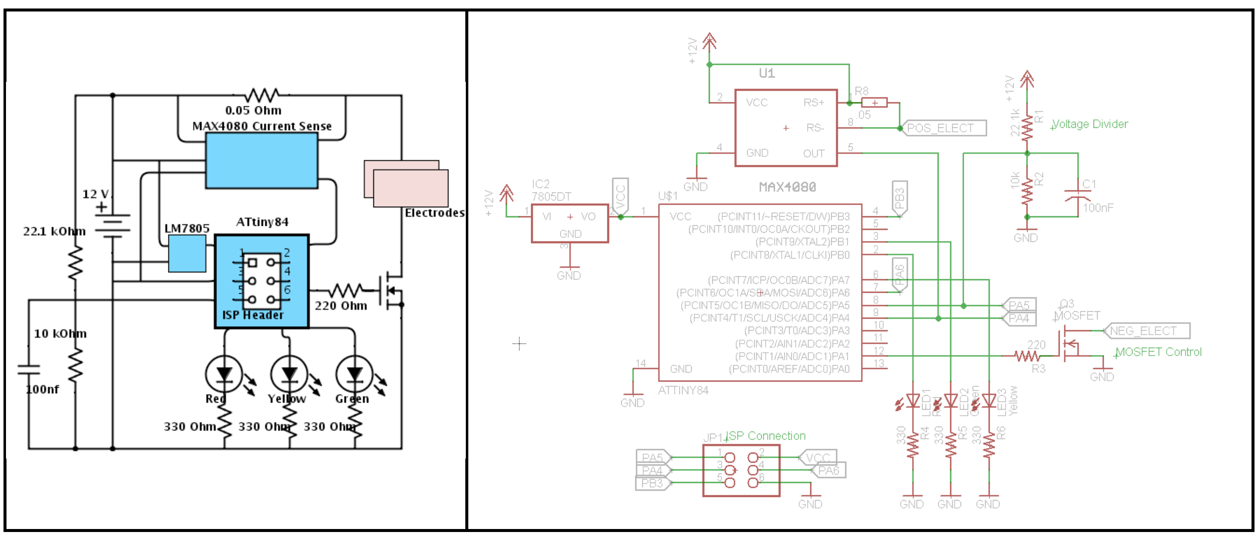


Figure M2: Circuit high level diagram and circuit schematic showing the ATtiny84 microprocessor and the peripheral components used to make measurements, control the current, and signal the user.

The circuit has been prototyped on a breadboard, shown to work, and designed as a printed circuit board in EAGLE. Figure L3 shows the board layout for the 1.5"x1.5" circuit board. The bottom holes are for the ground and +12V wires from the battery. The top two holes are for the wires going to the electrodes.

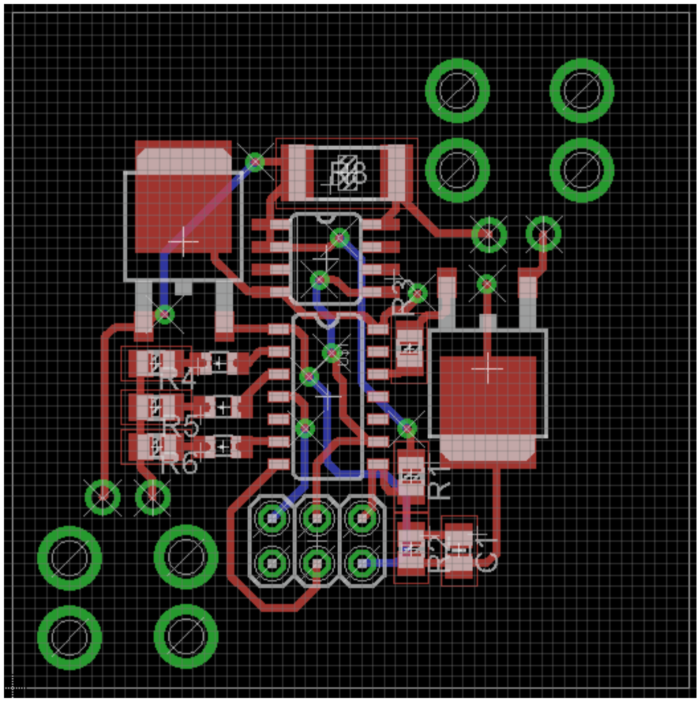


Figure M3: Board layout of the SafaPani control circuit on a 1.5”x1.5” board. Holes have been placed near the wire connections to allow wire straps to add strain relief to the wires.

Full Parts List for the Custom PCB

Item	Quantity	Description	Manufacture	Part Number	Manu Part Num	Package	/Unit for 1	/Unit for 1,000	/Unit for 5,000	/Unit for 1
330 Ohm Resistor	3	For LEDs	DigiKey	RMCF0805JT330RCT- N	RMCF0805JT330R	0805	0.1	0.00448	0.00266	0.00266
220 Ohm Resistor	1	For MOSFET	DigiKey	RMCF0805JT220RCT- N	RMCF0805JT220R	0805	0.1	0.00448	0.00266	0.00266
22.1k Ohm Resistor	1	For Voltage Divider	DigiKey	RMCF0805FT22K1CT- N	RMCF0805FT22K1	0805	0.1	0.00448	0.00266	0.00266
10k Ohm Resistor	1	For Voltage Divider	DigiKey	RMCF0805FT10K0CT- N	RMCF0805FT10K0	0805	0.1	0.00448	0.00266	0.00266
0.05 Ohm Resistor	1	Shunt Resistor	DigiKey	985-1217-1-ND	LR2512-R05FW	2512	0.81	0.32726	0.2275	0.2275
100nF Capacitor	1	For Voltage Divider	DigiKey	1276-1007-1-ND	CL21F104ZBCNNNC	0805	0.1	0.00783	0.00783	0.006
DIL 6 Pin Header	1	ISP connection	DigiKey	952-2121-ND	M20-9980346		0.23	0.1026	0.09405	0.09405
MAX4080 Current Sens	1	Current Sense Amp	DigiKey	MAX4080SAUA+-ND	MAX4080SAUA+	8-TSSOP	1.64	1.568	1.2852	1.2852
MOSFET	1	Logic Level Mosfet	DigiKey	RFD14N05LSM9ACT- ND	RFD14N05LSM9A	TO-252	0.99	0.39683	0.32468	0.32468
Microprocessor	1	ATtiny84 Microprocessor	DigiKey	ATTINY84A-SSURCT- N	ATTINY84A-SSUR	14-SOIC (0.154"Width)	1.8	0.83973	0.78275	0.78275
5 Volt Regulator	1	5 Volt Regulator	DigiKey	BA17805FP-E2CT-ND	BA17805FP-E2	TO-252-3	0.68	0.245	0.217	0.217
Green LED	1	Process over	DigiKey	160-1179-1-ND	LTST-C170GKT	0805	0.34	0.06318	0.05589	0.0486
Red LED	1	Battery low	DigiKey	160-1176-1-ND	LTST-C170CKT	0805	0.34	0.06318	0.05589	0.0486
Yellow LED	1	In Process	DigiKey	160-1175-1-ND	LTST-C170YKT	0805	0.34	0.06318	0.05589	0.0486
Wires		18 gage stranded wire								
Potting Epoxy			Alibaba	Kafuter K-9761						
PCB	1		Silver Circuits	http://www.custompcb.com			$1.09	$0.53	$0.46	$0.46
						Electronics Total	$8.76	4.22471	3.57732	3.55362

Table M1: A complete summary of all parts used to construct the SafaPani's PCB. The information includes the part, quantity, manufacturer, part number, and price.

Appendix N: Microprocessor Code

```
//**********************************************************************//
// SafaPani Firmware
// copyright VillageTech Solutions (www.villagetechsolutions.org)
// author: Steve and the Dartmouth 89/90 team - Winter 2015
//
// filename: SafaPaniFirmwareV1.ino
// compile with Arduino IDE
//
//**********************************************************************//



/*
This code is used to program an Arduino Nano, or an ATTiny84, to run an
electrolysis process for the SafaPani household arsenic water filter. It
uses a MOSFET transistor to turn on and off current through two iron
electrodes in water. It also senses the current through the electrodes
by using a MAX4080 current sense integrated circuit, and a shunt resistor.
*/

#include <elapsedMillis.h>        // from playground.Arduino.cc/Code/ElapsedMillis  Not a built-
in Arduino library. Must be installed in ..Arduino/Library
                                 // note: elapsedMillis library must be pre-loaded in the Arduino
IDE  for this include to work
                                 //   [see: http://playground.arduino.cc/Code/ElapsedMillis to
download the library,
                                 //   and  http://arduino.cc/en/Guide/Libraries for instructions
on installing the library in Arduino IDE]
#include <avr/power.h>            // Library of functions to disable peripherals on the ATTiny84
to limit the power usage
#include <avr/sleep.h>            // Library of functions to put the ATTiny in different levels
of sleep to limit the power usage

//**********************************************************************//
/*
// ARDUINO NANO PIN LOCATIONS: Enable when using the Arduino Nano as the microcontroller
// Digital Pin locations
const int green_led  = 7;                    // Pin to control the Green LED to signal when
process is complete.
const int red_led    = 9;                    // Pin to control the Red LED to signal when the
battery is low.
const int MOSFET_pin = 2;                    // Pin to control the MOSFET to switch on or off
current through the electrodes.

// Analog Pin locations
const int yellow_led = 8;                    // Pin to control the Yellow LED to signal when
process is running.
                                            // TODO: I changed pin to analog output for fading.
Choose an analog pin for the Yellow LED
const int voltage_divider_pin = A7;          // Pin to read the battery voltage with a voltage
divider.
const int current_pin         = A0;          // Pin to read the current through the electrodes
with a current sense amplifier.
*/
//**********************************************************************//



//**********************************************************************//
// ATTINY84 PIN LOCATIONS: Enable when using the ATTiny84 as the microcontroller
// Digital Pin locations
const int green_led  = 0;                    // Pin to control the Green LED to signal when
process is complete.
const int red_led    = 1;                    // Pin to control the Red LED to signal when the
battery is low.
```

```
const int MOSFET_pin = 9;                    // Pin to control the MOSFET to switch on or off
current through the electrodes.

// Analog Pin locations
const int yellow_led         = 3;            // Pin to control the Yellow LED to signal when
process is running.
const int voltage_divider_pin = 5;           // Pin to read the battery voltage with a voltage
divider.
                                            // Note: You must use a pin that is analog input
capable.
const int current_pin         = 7;           // Pin to read the current through the electrodes
with a current sense amplifier.
                                            // Note: You must use a pin that is analog input
capable.
//***********************************************************************//



// LED Parameters
int yellow_led_brightness  = 0;              // Variable to keep track of how bright the Yellow
LED is
int yellow_led_fade_amount = 1;              // Variable to keep track of how fast the Yellow
LED fades

// Variables dealing with the charge across the electrodes
float coulomb_count     =    0;              // Coulombs of charge that have passed through the
electrodes. Initialize at 0.
//const int coulomb_limit = 105000;         // TODO:(Determine Correct coulomb limit correlated
to iron in water).
                                            // Coulomb limit that signals that Electrolysis is
over. (Coulombs)
const int coulomb_limit =    5;                   // TESTING VALUE. Coulomb count setting to be
able to test over short timeframe. (Coulombs)
const float Rshunt      = 0.05;                   // Shunt resistor value (Ohms). Used to
convert Current sense output voltage to current.

// Variables to keep track of interval times
const long           sample_time =   10000;   // Time interval between current calculation (ms).
const long              mix_time = 1000000;   // TODO:(Determine correct mix time) Time to wait
after electrolysis (ms).
const long   battery_sample_time =   20000;   // Time interval between battery voltage checks
(ms).
const int     red_led_pulse_time =    1000;   // Time interval between Red LED toggles when the
battery is low (ms).
const int yellow_led_update_time =      60;   // Time interval between Yellow LED fade updates
(ms).

// Variables used to keep track of time elapsed
elapsedMillis timeSinceCurrentCheck     = 0;  // Variable to keep track of how long since the
current has been checked
elapsedMillis timeSinceYellowLEDUpdate  = 0;  // Variable to keep track of how long since Yellow
LED fade amount has been updated
elapsedMillis timeSinceBattCheck        = 0;  // Variable to keep track of how long since the
battery has been checked
elapsedMillis timeSinceLowBattLEDUpdate = 0;  // Variable to keep track of how long since Red LED
has been updated

// Variables to convert ADC values into actual voltages
const int bitt = 1024;                       // Amount of bits output from the ADC
const int VSS  = 4600;                      // Max voltage used to scale the ADC output to a
voltage (mV)
                                            // TODO: Check if this value is correct. I found
this value in the code sent to the Dartmouth 89/90 Winter 2015 team

// Battery Voltage Parameters
float              battery_voltage  =    12; // Declare a variable to hold the current battery
voltage (Volts). Initialize to 12 to make smoothing work
const float       low_battery_limit  =  11.5; // TODO: (Determine low battery limit) Low battery
voltage limit (Volts)
```

```
const float power_off_battery_limit  =    11; // TODO: (Determine absolute lowest battery limit)
Power off battery voltage limit (Volts)
boolean                     lowBatt  = false; // Initialize boolean to signal when the battery is
getting low (below low_battery_limit).
const float   voltage_divider_ratio  =  3.21; // R1=10kOhms, R2=22.1kOhms, Battery Ratio-
>Divider=R1/(R1+R2). Divider->Battery Ratio=(R1+R2)/R1 = 3.21
                                             // This value is used to scale the voltage read from
the voltage divider to the actual battery voltage

////////////////////////////////////// Setup //////////////////////////////////////////
// the setup routine runs once the device is turned on or a reset is pressed:
void setup()
{
 delay(1000); // Wait one second for transient currents to die out

 // Ensure no floating pins to help save power ( ATTINY84 Specific )
 for(int i=0; i<12 ; i++)
 {
   //pinMode(i, OUTPUT);
   //digitalWrite(i, LOW);
 }

 // Configure the pins of the microcontroller as input and output
 pinMode(voltage_divider_pin, INPUT);
 pinMode(current_pin, INPUT);
 pinMode(green_led, OUTPUT);
 pinMode(yellow_led, OUTPUT);
 pinMode(red_led, OUTPUT);
 pinMode(MOSFET_pin, OUTPUT);

 // Power saving settings
 //power_adc_disable();                        // Disable the ADC. Will be enabled when used.
 //power_usi_disable();                        // Disable universial serial bus
 //power_timer1_disable();                     // Disable timer 1 as it is not used

 //Serial.begin(9600);
 //Serial.println("time Curr Volt Cul");
}//end setup()

////////////////////////////////////// Main Loop ////////////////////////////////////////
// The loop routine runs over and over again forever:
void loop()
{
 // Battery Monitoring  -- when low battery is detected, pulse red LED every 2 seconds
 // Check the battery voltage every "battery_sample_time" seconds
 batteryCheck();

 digitalWrite(MOSFET_pin, HIGH);                    // Turn on the current to electrodes

 float instantaneous_current = check_current();     // Calculate the instantaneous current
through the electrodes (Amperes)

 // Integrate the current to update Coulomb count
 // TODO: Fix a bug to correctly calculate the amount of coulombs that have flown across the
electrodes
 coulomb_count += instantaneous_current * ( (float)sample_time / 1000);  //TESTING



 // If enough charge has passed, stop the electrolysis process, and start waiting "mix_time" for
mixing
 if( coulomb_count >= coulomb_limit )
 {
   electrolysis_process_complete();                 // Wait mix_time, and then signal process is
complete
 }
```

```
 // TODO: Record the time, current, and cumulative charge
 //record_data(current);

 // Wait "sample_time" seconds from the the previous time through the loop to save battery.
 // Blink the yellow and Red LEDs as appropriate.
 wait_and_blink( sample_time );

} // end loop()

/////////////////////////////////////// Functions ///////////////////////////////////////////

// Fade Yellow LED according to "yellow_led_fade_amount" to signal that the process is active.
// Fade faster during mixing, as the process is almost over.
void update_yellow_led()
{
 // If enough time has passed. Update the Yellow LEDs fade amount
 if(timeSinceYellowLEDUpdate > yellow_led_update_time)
 {
   // Reset Yellow LED Update time
   timeSinceYellowLEDUpdate -= yellow_led_update_time;

   // Update LED brightness
   yellow_led_brightness += yellow_led_fade_amount;

   // Fix any out of bounds problems
   if (yellow_led_brightness >= 20)
     yellow_led_brightness = 20;
   else if (yellow_led_brightness <= 0)
     yellow_led_brightness = 0;

   // Reverse the direction of the fading at the edges of fade voltages:
   if (yellow_led_brightness == 0 || yellow_led_brightness == 20) {  // TODO: determine max led
brightness (20 seems to give a qualitative max brightness)
     yellow_led_fade_amount = -yellow_led_fade_amount ;
   }

   // Set the Yellow LED to a new brightness
   analogWrite(yellow_led, yellow_led_brightness);
 }
} // end update_yellow_led()

// If the battery is low, and red_led_pulse_time has elapsed, toggle the Red LED
void update_red_led()
{
 if(lowBatt && (timeSinceLowBattLEDUpdate > red_led_pulse_time) )
 {
   timeSinceLowBattLEDUpdate -= red_led_pulse_time; // Reset the timeSinceLowBattLED counter

   // Toggle the Red led
   if(digitalRead(red_led) == LOW)
     digitalWrite(red_led,HIGH);
   else
     digitalWrite(red_led,LOW);

 }// end IF LOWBATT
} // end update_red_led()

// Calculate the instantaneous current through the electrodes
float check_current()
{
 //power_adc_enable();                                 // Enable the ADC
 float current_val = analogRead(current_pin);        // Read the value from the current sense
amplifer
 //power_adc_disable();                                // Disable the ADC
```

```
 current_val = map( current_val, 0, bitt, 0, VSS );    // Map the binary value read to between 0
and VSS (mV)
 current_val = current_val / 1000;                     // Convert the current_val from mV to
Volts
 float current = current_val / (Rshunt * 60.0);        // Calculate the current using the shunt
resistor, and an amplifier scalar of 60
 return current;
} // end check_current()


// Check the battery level every battery_sample_time seconds.
// Set lowBatt if battery is low and power off if battery is very low.
void batteryCheck()
{
 if(timeSinceBattCheck > battery_sample_time)          // Check battery every battery_sample_time
seconds
 {
   timeSinceBattCheck -= battery_sample_time;          // Reset the time since the battery was
checked

   battery_voltage = 0.5*(double)battery_voltage + 0.5*(double)readVcc(); // Update Vcc reading
with smoothing

   if(battery_voltage < low_battery_limit)             // threshold set at low_battery_limit for
low voltage indication
   {
     lowBatt = true;                                   // Set lowBatt threshold
     while(battery_voltage < power_off_battery_limit)  // threshold set at
power_off_battery_limit to power off if battery too low
     {
       //goToSleep();                                  // TODO: Should we just shut the whole
device off and wait for reset here?
                                                       //       i.e. jump to low_battery()
function
       battery_voltage = readVcc();
     }

   } else {
     lowBatt = false;                                  // If the battery voltage is above
low_battery_limit, set lowBatt as false
   }
 }
} // end batteryCheck()

// Calculate the battery voltage by scaling the value read from the voltage divider
double readVcc()
{
 //power_adc_enable();                                                    // Enable the ADC
 int sensor_val = analogRead(voltage_divider_pin);                       // Read the "voltage
divider" analog pin
 //power_adc_disable();                                                   // Disable the ADC
 double voltage_divider_voltage = map( sensor_val, 0, bitt, 0, VSS );      // Calculate voltage
(mV) at the voltage divider
 voltage_divider_voltage = voltage_divider_voltage / 1000.0;              // Convert from
millivolts to Volts
 double battery_voltage = voltage_divider_voltage * voltage_divider_ratio; // Convert "voltage
divider" voltage to battery voltage
 return battery_voltage;
} // end readVcc()


// Battery is too low to continue electrocoagulation
// Turn on the Red LED and wait until device is shut down
// TODO: CURRERNTLY NOT USED. Should we jump here if battery is too low to continue?
void low_battery()
{
 // Turn off the current to electrodes
 digitalWrite(MOSFET_pin, LOW);
```

```
 // Turn off Green and Yellow LEDs
 digitalWrite(green_led, LOW);   // Turn off Green LED (should already be off)
 digitalWrite(yellow_led, LOW);  // Turn off Yellow LED

 // Turn Red LED on
 digitalWrite(red_led, HIGH);

 // Wait until device is shut off
 wait_for_shutdown();
} // end low_battery()

// Electrolysis is done. Turn off current to electrodes, wait mix_time while blinking
// the Yellow LED, and then turn on the Green LED and wait for device to be shut off
void electrolysis_process_complete()
{
 digitalWrite(MOSFET_pin, LOW);  // Reaction over. Turn off the current to electrodes

 yellow_led_fade_amount *= 2;    // Double the speed of the Yellow LED fading
 wait_and_blink( mix_time );     // Wait for iron and arsenic to mix and react

 // Mixing over, light the Green LED and shut off the Yellow and Red LEDs
 digitalWrite(yellow_led, LOW);  // Turn off Yellow LED
 digitalWrite(red_led, LOW);     // Turn off Red LED
 digitalWrite(green_led, HIGH);  // Turn on Green LED

 // Wait until device is shut off
 wait_for_shutdown();
} // end electrolysis_process_complete()

// TODO: Data recording
// Record data values for later analysis
void record_data( int current )
{
 float time = millis();
 time = time/1000.0;

 Serial.print(time);
 Serial.print(" ");
 Serial.print(current);
 Serial.print(" ");
 Serial.print(coulomb_count);
 Serial.print(" ");
} // end record_data()

// Wait time_to_wait seconds while still blinking the yellow LED
void wait_and_blink( long time_to_wait )
{
 // Wait for time_to_wait to pass while Fading the yellow LED
 while( timeSinceCurrentCheck < time_to_wait )
 {
   // Fade the Yellow LED if enough time has passed
   update_yellow_led();

   // If the battery is low, and red_led_pulse_time has elapsed, toggle the Red LED
   update_red_led();
 }
 // Reset timeSinceCurrentCheck
 timeSinceCurrentCheck = 0;
} // end wait_and_blink()

// Simply loop until the device is shut down
void wait_for_shutdown()
{
 // Turn on the appropriate LEDs
 digitalWrite(yellow_led, LOW);  // Turn off Yellow LED
```

```
  digitalWrite(green_led, LOW);   // Turn off Green LED
  digitalWrite(red_led, HIGH);    // Turn on Red LED

  power_all_disable();            // Disable all peripherals

  // TODO: Go to sleep here? We still want the Red LED lit up
  while(1) {}                     // Wait for a full reset
} // end wait_for_shutdown()
```

Appendix O: Working Prototype Assembly

	1. Empty 14 gallon, taper-sided chemical container
	2. Fill bottom with 1” of marbles to fill in depressions and to increase surface area for water flow.
	3. Add sandscreen and 8 inches of sand.
	4. Cut 2.5” diameter hole in 4 gallon bucket for flapper valve and drill two small holes for nylon screws to secure velcro for electrode holders. Order of assembly on screw: 1” rubber washer, velcro, put through hole in bucket, 1” rubber washer, finish with nylon nut. Next, place one rubber o-ring around each iron bar and then strap the pair of bars in with velcro.
	5. File two channels in rim of reaction vessel. One for electrode wires, and the other for the flapper pull cord.

Figure O1: Assembly instructions for the working prototype.

Appendix P: Working Prototype Bill of Materials

Working Prototype Bill of Materials			
Item	Description	Quantity	Price
Shell	15 Gallon Chemical Container	1	$34.56
Reaction Vessel	5 Gallon Horse Feed Bucket	1	$17.95
Reservoir	Cost of off the shelf tank in India	1	$10.00
Iron Electrodes	Raw material needed for electrocoagulation process	2.84 lbs	$0.29
Velcro	Secures electrodes	2 x 5 in. paired strips	$1.67
Flapper Valve	Allows resealable connection between reaction vessel and sand filer	1	$7.00
8-32 Nylon Screw	Secures electrode holder to reaction vessel	4	$0.22
8-32 Nylon Nut	Secures electrode holder to reaction vessel	4	$0.24
8-32 Screw	Attach wires to electrodes	2	
Rubber Washers	Seal screw hole in reaction vessel	8	$2.40
0.06" PETG Sheet	Thermoformed Lid: Covers reaction vessel to prevent debris entry	0.06" x 14" x 14"	$2.85
String	Secures lid when refilling reaction vessel	4"	$0.20
1/8" Thick Acrylic Sheet	Dispersion Plate: Disperses water over sand filter to prevent channeling Sand Screen Holders: Secures and supports nylon fabric sand filter	1/8" x 27" x 27"	$12.66
Marbles	Provides stable, porous platform to support the sand filter	5 lbs	$9.31
1/2" Bulkhead Adapter	Connection between the shell and reservoir	1	$11.07
Nylon Fabric	Fabric used for sand screen	12.5" x 12.5"	$0.81
Neoprene Rubber Tubbing	Provides watertight seal for sand screen	1/4" ID x 1/2" OD x 3.2' long	7.36
Gorilla Glue	Adhesive used to construct and seal sand screen	15 mL	$0.10
Electronics	Total cost for all electronic components in device		$4.81
Sand	Sand used to filter arsenic-iron precipitate	50 lbs	$3.69
		Total	$127.19

Figure P1: Bill of materials for the working prototype.

Appendix Q: State of the Art Analysis

Figure Q1: Left: SONO Filter set up in a Nepalese home. Right: Kanchan Filter being used by a Nepalese woman.

There are currently many different arsenic filtration products on the market, varying in filtration method and size. Examples of filters currently on the market include the household- sized SONO Filter, ALCAN Filter, READ-F Filter, Kanchan Arsenic Filter, and the community- sized SIDKO plant. However, after consulting with previous SafaPani team member Chad Piersma and Dartmouth Humanitarian Engineering leader Meili Eubank, both of whom have conducted a field study of the heavily affected Nawalparasi district of southern Nepal, two main competitors of the SafaPani device stood out: the SONO Filter by Filters for Families (FFF) and the Kanchan Filter by the Environmental and Health Organization in Nepal (ENPHO).

Both filters use an arsenic absorption process through the means of a composite iron material. The SONO Filter is a two-bucket system that uses a bed of iron fillings to react with arsenic and a bed of sand to filter the water. The Kanchan Arsenic Filter consists of a top bucket full of rusty nails and brick chips that is suspended over a sand filter with a piping assembly at the bottom of the bucket. The filter uses the pressure in the system to pump water into an outside collection container.

While both designs successfully filter arsenic, they both have shortcomings. The Kanchan filter not only requires many parts and a complex assembly, but also suffers from an incredibly slow flow rate that continues to decrease as the sand filter quickly becomes clogged with precipitates. Additionally, both filters were often found abandoned by users after small protruding valves or piping acquired minor damage from minor accidents in the home. Disregarded maintenance procedures and inefficient subsidies by both ENPHO and FFF have given no incentive for users to maintain or repair their filter, nor the opportunity to purchase new ones (Piersma 2013). Therefore, a robust, inexpensive design coupled with a well-designed marketing and business model is needed to successfully implement the SafaPani technology into Nepali households.

Appendix R: Expert Consultations

Expert Consultation Meetings and Topics		
Technical Consultant	**Expertise**	**Topics**
Dartmouth Humanitarian Engineering (DHE) and Previous 89/90	Previous work on project	Problems with existing prototype. Current Nepalese water use.
Jim Hall	Lean Six Sigma black belt. Principal consultant for ITM Consulting	Minimize number of parts and complexity. Minimize detachable parts. Tolerances.
Dana Howe	Cost and Systems Engineer at injection molding company G.W. Plastics	Injection molding is significantly more expensive than blow or roto molding. RV water tanks may meet our need for clean water reservoir.
Peter Robbie	Human-centered and product design	Investigate how pre-existing parts are manufactured. Draft angles. Injection/rotational/blow molding. Design process.
Kevin Baron	Design processes	Cost cutting. Rolled sheet vs. tube. Thermoforming.
Ron Lasky	Professor of Cost Estimation	Materials and processes in India can be considered the same as U.S. Account for all NRE costs. Analog vs. digital electronics.
Ulrike Wegst	Professor of Materials	Cambridge Engineering Selector (CES) software. Material selection.
Mike Kokko	Senior Systems Integration Engineer at Simbex	Chamfer for assembly. Pressure for seal. Seal options and tolerances. Keep LED inside the bucket. Device Master Record (DMR).
Jaydeep Dasgupta	Manufacturing Contact in India	Asked for pricing on our reservoir design. Asked for local prices of materials.
Ranjiv Khush	CEO and co-Founder of Aquaya (R&D Organization for Water Filters for Low Income Countries)	Desire to pay indirectly proportional to required user input. Large social issue.
John Keller	Blow Molder at Blow Molded Specialties	Awaiting response of quote.
Steven Montville	Mold Engineer at Rocheleau Blow Molding	Agreed to look at our design. SolidWorks drawings were sent, but still awaiting response.
Mike Jakiela	Rotomolder at Sterling Industries	Quote for rotational mold. $14,000 for our SolidWorks design of reservoir. Price per piece is $82.25.
Vicki May	Professor of Structural Mechanics	Stability and strength of design. Suggested horizontal ribbing as support for reservoir.

Table R1: A summary of the consulted experts, their specialty, and the major takeaways.

Appendix S: CES Analysis

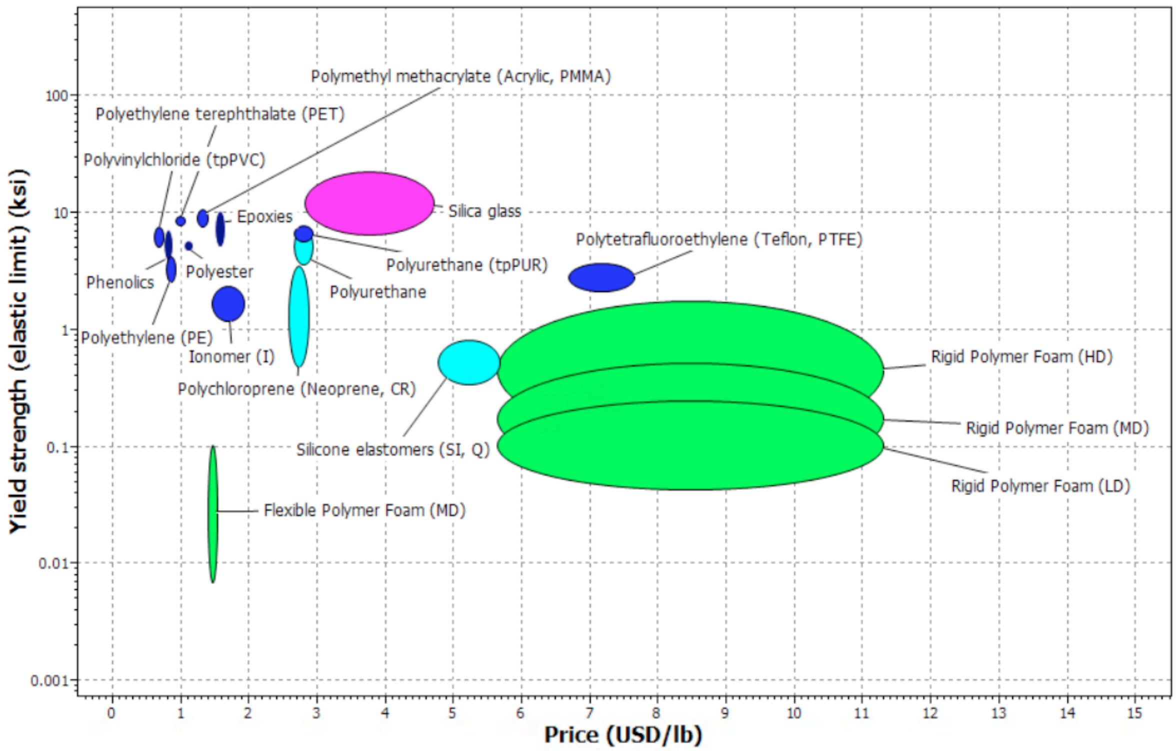


Figure S1: CES software plotting yield strength over price for materials that are good insulators, have excellent durability when submerged in freshwater, have excellent durability in a rural atmosphere, have fair durability in UV radiation (sunlight), and less than 137 lb/ft^3 density.